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An HF Antenna for Oblique Propagation Having Approximately Circular Polarization Over Appreciable Frequency and Vertical-Angle Intervals

by

J. M. Lomasney
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TECHNICAL REPORT NO. 153

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RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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ABSTRACT

This report describes the design of a pair of HF antennas, one horizontally and one vertically polarized, whose gains and directivity patterns are reasonably alike over the range of elevation angles useful for oblique ionospheric propagation over typical one-hop distances. Means are given for obtaining the proper phasing for approximating circular polarization at a designated elevation angle and over a substantial frequency interval. The design must take into account the differing reflecting properties of ordinary ground for vertically-polarized and horizontally-polarized incident waves, and the variations of these properties with radio frequency.

The theoretical performance of a cross-polarized antenna pair of one particular configuration is described. It is shown that satisfactory performance should be obtained over ground having electrical properties within the range usually encountered, though not when the reflecting surface is fresh water, sea water or ground covered by a conducting screen.

Experimental results are given which tend to confirm that the crossed antenna pair does operate in the manner predicted by the theory. Construction details are furnished.

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ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of other members of the Ionospheric Dynamics Group, especially the encouragement and guidance of Professor O. G. Villard, Jr. The equations for the reflection coefficients of ordinary ground and for many of the antenna patterns were programmed by Mr. Douglas Westover, and those for water and ground screen by Mr. David Bubenik. Many helpful suggestions regarding the mechanical design, modification and erection of the antennas were given by Mr. Kenneth Johansen. The special mountings and parts required were fabricated by the Stanford University Service Group under Mr. George Green.

I. INTRODUCTION

A. PURPOSE

The purpose of the research described in this report was to design a pair of HF antennas, one horizontally and the other vertically polarized, whose gains and directivity patterns would be reasonably alike. Such a pair of antennas would be useful for studies in oblique-incidence HF ionospheric propagation, and could also be of interest to communicators and other users of the HF spectrum, e.g., for polarization diversity reception.

Additionally, the phase characteristics of the two antennas were to be sufficiently well matched so that they could be used to approximate circular polarization. This would widen their application considerably for studies of propagation, and possibly for other uses as well.

B. PAST WORK IN THE FIELD

The notion of providing pairs of cross-polarized antennas is quite old, especially for such uses as polarization diversity. No attempt will be made to provide a complete survey of previous work, but a few instances of application at HF will be cited.

Kennedy and Ames [Ref. 1] describe a commercially available system consisting of a vertically polarized log-periodic dipole array and a similar horizontally polarized array, suspended from two towers. As the intended use of the antennas was for polarization diversity reception, the principal concern was for the orthogonality of their polarizations, and (to quote Ref. 1) "the two arrays probably had equal sensitivity at about

15 deg to 20 deg above the horizon." The relative sensitivity at other elevation angles and the phase relationship are not mentioned. A number of other useful references are cited by these authors.

Gerst and Worden [Ref. 2] describe a multifilar contrawound helix antenna which can provide linear or circular polarization. It appears that, for circular polarization, antennas of this type are intended for operation remote from ground. A half-helix configuration is described which operates against a ground plane, but produces only linear polarization; also, an essentially perfectly conducting plane appears to be required. Again, other useful references are cited in the article.

An interesting application of an orthogonal pair of antennas to reduce skywave fading in the medium-frequency region is described by J. M. Dixon of the Australian Broadcasting Control Board [Ref. 3]. A broadcast-type vertical antenna was used in conjunction with a horizontal dipole to provide an elliptically-polarized signal. The amplitudes and phases of the horizontal and vertical components were adjusted to excite the extraordinary mode of propagation via the nocturnal E layer. Since the referenced article is only a digest of the original work, it does not describe the method of computing the antenna patterns, but apparently the properties of the reflecting surface were taken into account.

Hedlund and Edwards [Ref. 4] describe an experiment using a horizontal and a vertical antenna at the same height. Only amplitude data were recorded, and the relative phases of the H and V components of the received signal were deduced from the relative amplitudes. In this application the absolute phase and amplitude relationships between signals present at the horizontal and vertical antenna terminals were of lesser importance than for some other applications.

C. WORK AT STANFORD UNIVERSITY

1. Design Approach

Most of the earlier work at Stanford Electronics Laboratories (SEL) with antennas of controllable polarization was in the VHF range and at high elevation angles, such as for satellite and planetary studies, where ground reflection was of no consequence. One investigation in the HF region used a pair of crossed dipoles oriented at ±45 deg from the vertical (Fig. 1). Measurements showed, however, that the polarizations of the two antenna patterns were far from orthogonal, because of the disparate effect of ground reflection.

In January 1967 an investigation was begun by M. R. Epstein, at that time associated with SEL, into polarization of ionospherically propagated waves [Refs. 5, 6]. The need for an orthogonal pair of HF antennas of wide bandwidth for use in this experiment became apparent. Various possible configurations were considered. In discussions with Dr. O. G. Villard, Jr. it was decided to examine the possibility of using horizontally polarized and vertically polarized antennas located at different heights. It was found empirically that at the lower elevation angles which were of principal interest, placing the horizontal antenna at 0.71 the height of the vertical antenna should give good coincidence of the elevation amplitude patterns over a range of frequencies.

It was also realized that circular polarization, both right- and left-hand, should be obtainable from the linearly cross-polarized pair by the use of phasing networks or lines and a sum/difference combining hybrid [Ref. 7]. By adding two power splitters, four outputs could be made available simultaneously, having respectively right-circular, left-circular, horizontal and vertical polarizations.

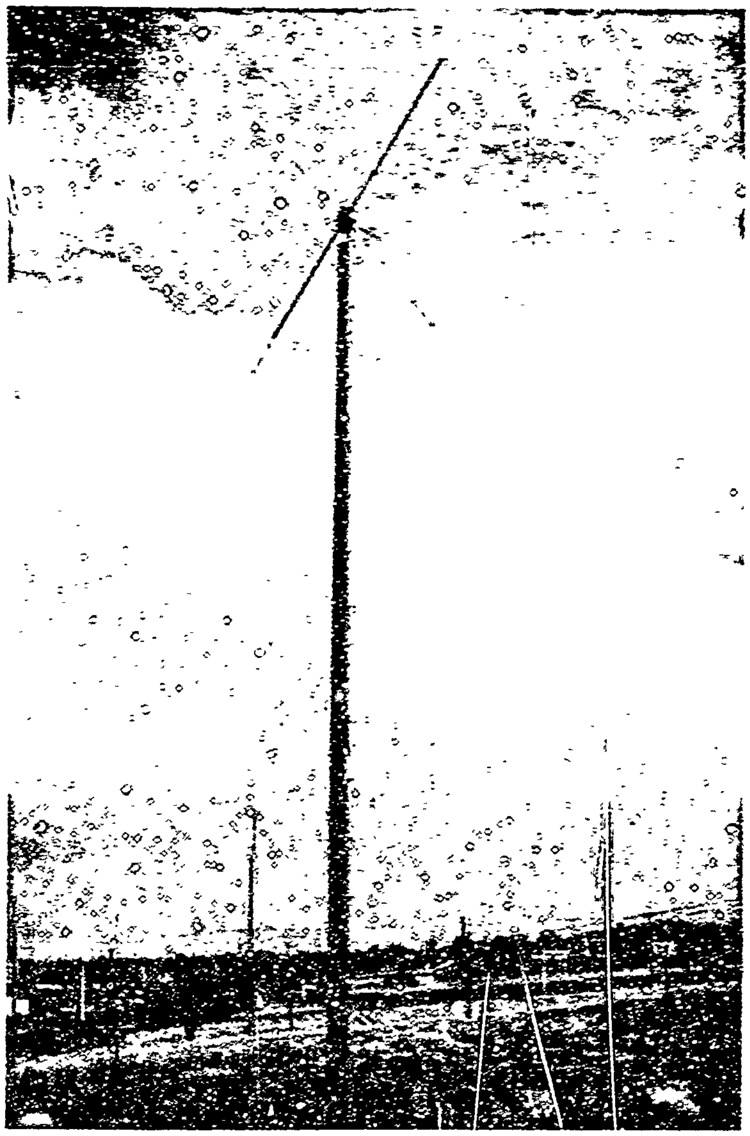

Figure 1. Pair of crossed dipoles oriented at ±45 deg frcm the vertical.

The phase relationship between the radiated fields of the horizontal and vertical antennas was investigated in some detail as a function of elevation angle, so that the length of phasing cable required to give circular polarization at any selected angle and frequency could be found. A computer program for calculating elevation patterns with various ground constants and antenna parameters was made up, and a selection of patterns was computed.

2. The Prototypes

To obtain the desired band coverage, log-periodic antennas (LPA's) of a type already in use were selected. Modifications were made to adapt one of the usually horizontally polarized antennas for mounting in the vertical plane, and erection of the first prototype antenna pair was begun at a site on the Stanford campus. The pair was aimed in an eastward direction.

Experiments were begun in March, 1967, using transmissions from Lubbock, Texas. Results were encouraging. A second antenna pair, pointing in the direction of Stanford, was installed at Lubbock at the end of May.

The crossed-antenna pair was removed from Lubbock in August 1967, and was re-erected at the Stanford field site at Lost Hills, California in October of the same year. It was aimed in an eastward direction. In January 1969 a second antenna pair was installed at the Lost Hills site, pointing westward over the Pacific Ocean. At the present time the two antenna pairs provide a choice of eastward or westward operation. A crossed-antenna pair was installed at Stanford's Bearden, Arkansas field site in June 1969, aimed in the direction of the Stanford field site at Los Baños, California.

3. Summary

The present report discusses the properties of ground as a reflector and describes a method, developed at Stanford University and applicable to many types of antennas, for compensating for the effect of ground. In addition, the report describes the construction of a particular antenna pair (discussed above) which uses commercially available antennas and of which several examples have been built.

While complete pattern measurements on these antennas have not been made, the results of computer simulations and field experiments which have been performed with them tend to verify that the antennas perform essentially as predicted by theory.

II. TECHNICAL BACKGROUND: COMPUTED PERFORMANCE OF HORIZONTALLY POLARIZED AND VERTICALLY POLARIZED ANTENNAS

A. REFLECTION OF RADIO WAVES FROM THE GROUND

The basic difficulty in designing a pair of antennas in which both antennas are to have similar radiation patterns, except that one pattern is horizontally polarized and the other vertically polarized, is that the effect of ground reflection on the antenna elevation patterns is quite different for vertical than for horizontal polarization. At VHF and higher frequencies it is often possible to mount the antennas far enough above ground and to make them sufficiently directive so that ground reflection may be neglected, especially since the effect of ground conductivity decreases with increasing frequency. In the HF region, however, it is ordinarily not practical to avoid ground reflection, so that the design of the cross-polarized pair must take the properties of the ground into account.

Elevation-angle directivity patterns commonly found in the literature are for antennas over an ideal, perfectly-conducting plane. After reflection from such a plane, a horizontally polarized incident wave experiences a 180 deg phase shift and no loss in amplitude, while a vertically polarized wave is reflected with no phase shift or loss in amplitude. This is not true for antennas operating over real ground, but the approximation is sufficiently accurate for many purposes. For the purpose of designing crossed antennas suitable for radiating a circularly polarized field, more detailed knowledge of the phase and amplitude relationships between the vertically and horizontally polarized components is needed. The reflecting properties of actual ground must therefore be considered. These depend on the conductivity and permittivity of the ground, and on the elevation angle of the incident wave. Also, the effect of ground conductivity on the reflecting properties depends inversely on frequency, so that for actual ground the ideal-conducting-plane approximation becomes very poor as the frequency increases toward the upper end of the HF range.

B. ELECTRICAL PROPERTIES OF GROUND

The conductivity σ and relative permittivity ϵ_r (dielectric constant) of various types of ground, collected from various sources [Refs. 8, 9] are shown in Fig. 2. For purposes of this report typical value may be summarized as follows:

1. "Poor" ground, $\sigma = 10^{-3}$ to 10^{-4} mhos/meter, $\epsilon_r = 3$ to 5
2. "Good" ground, $\sigma = 10^{-2}$ mhos/meter, $\epsilon_r = 10$ to 15
3. Fresh water, $\sigma = 8 \times 10^{-3}$ mhos/meter, $\epsilon_r = 80$
4. Salt water, $\sigma = 4$ mhos/meter, $\epsilon_r = 80$

For both "good" and "poor" ground, the conductivity is small in the HF region, and in most cases the ground may be considered as a lossy dielectric. For fresh water the dielectric constant is large, but the conductivity is seldom large enough to be taken into account. For sea water the conductivity is large and the dielectric constant may usually be neglected. These concepts will be examined in greater detail in the next section. The effects on the ground-reflection properties caused by water or ground screen will be considered in Section K.

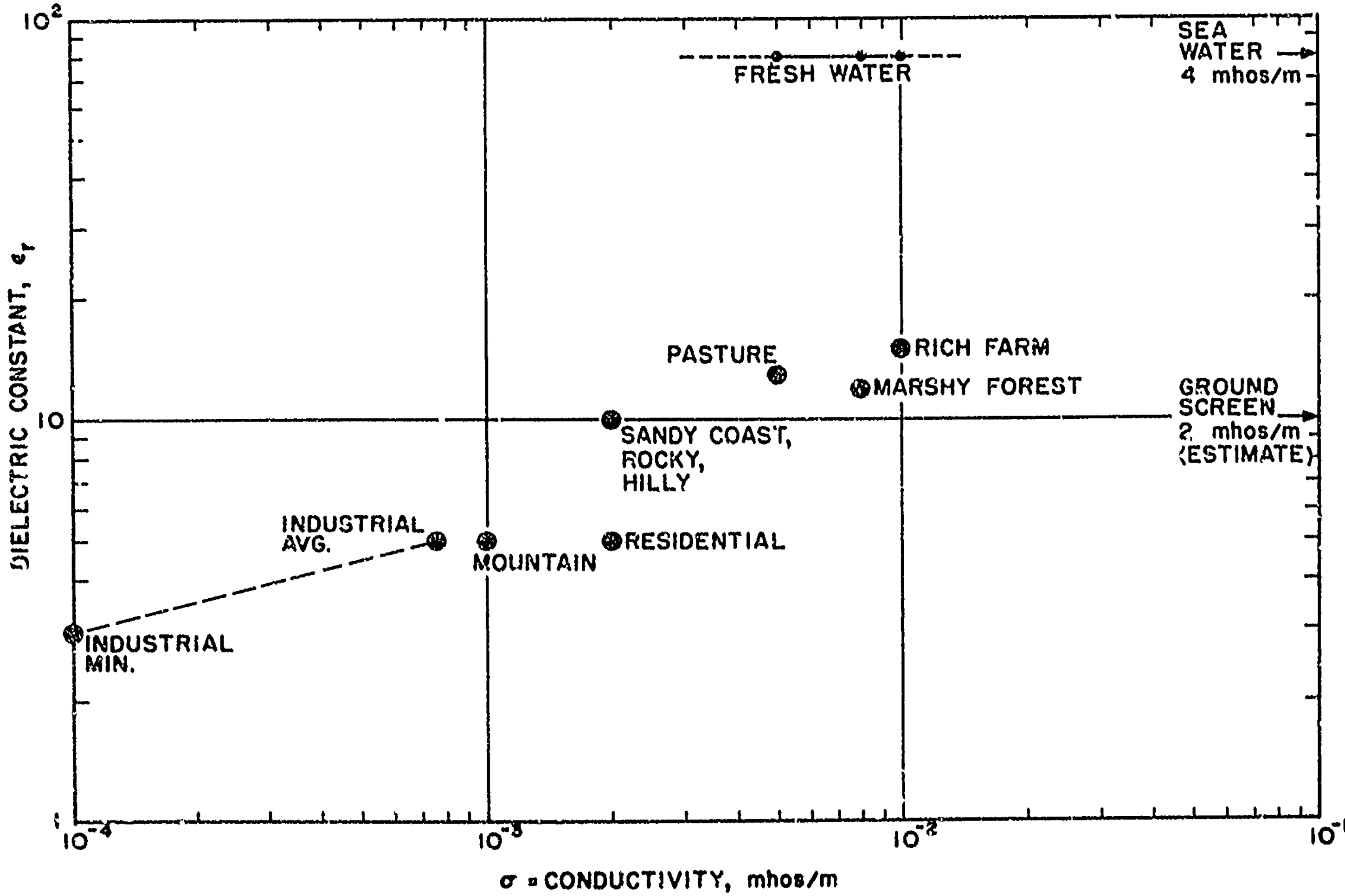

Figure 2. Electrical characteristics of various types of terrain (from I.T.T. Handbook, 4th edition, and Terman Radio Engineering, 4th edition).

C. THE REFLECTION COEFFICIENT

The problem of a wave obliquely incident on the plane interface between two lossy dielectric half-spaces has been considered by many authors, for example Skilling [Ref. 10], Weeks [Ref. 11], and Ohman [Refs. 12, 13]. Figure 3 illustrates the geometry of wave reflection and refraction, where the elevation angle of incidence, ψ_1, equals the angle of reflection, ψ_3, and the complement angle of refraction, ψ_2, differs from ψ_1 according to Snell's law. In terms of ψ_1, previous investigations have resulted in equations for the reflection coefficient, ρ, of the form:

(For Horizontally Polarized Incident Electric Field)

$$\rho_h = \frac{\sqrt{\dfrac{\epsilon_1}{\mu_1}} \sin \psi_1 - \sqrt{\dfrac{\epsilon_2}{\mu_2}} \sqrt{1 - \dfrac{\mu_1 \epsilon_1}{\mu_2 \epsilon_2} \cos^2 \psi_1}}{\sqrt{\dfrac{\epsilon_1}{\mu_1}} \sin \psi_1 + \sqrt{\dfrac{\epsilon_2}{\mu_2}} \sqrt{1 - \dfrac{\mu_1 \epsilon_1}{\mu_2 \epsilon_2} \cos^2 \psi_1}} , \tag{1}$$

(For Vertically Polarized Incident Electric Field)

$$\rho_v = \frac{\sqrt{\dfrac{\mu_1}{\epsilon_1}} \sin \psi_1 - \sqrt{\dfrac{\mu_2}{\epsilon_2}} \sqrt{1 - \dfrac{\mu_1 \epsilon_1}{\mu_2 \epsilon_2} \cos^2 \psi_1}}{\sqrt{\dfrac{\mu_1}{\epsilon_1}} \sin \psi_1 + \sqrt{\dfrac{\mu_2}{\epsilon_2}} \sqrt{1 - \dfrac{\mu_1 \epsilon_1}{\mu_2 \epsilon_2} \cos^2 \psi_1}} , \tag{2}$$

where μ_1 and μ_2 are the absolute permeabilities of the two media; and ϵ_1 and ϵ_2 are the absolute permittivities.

These equations are often given in terms of the optical angle of incidence θ_1 measured from the normal to the plane, rather than the

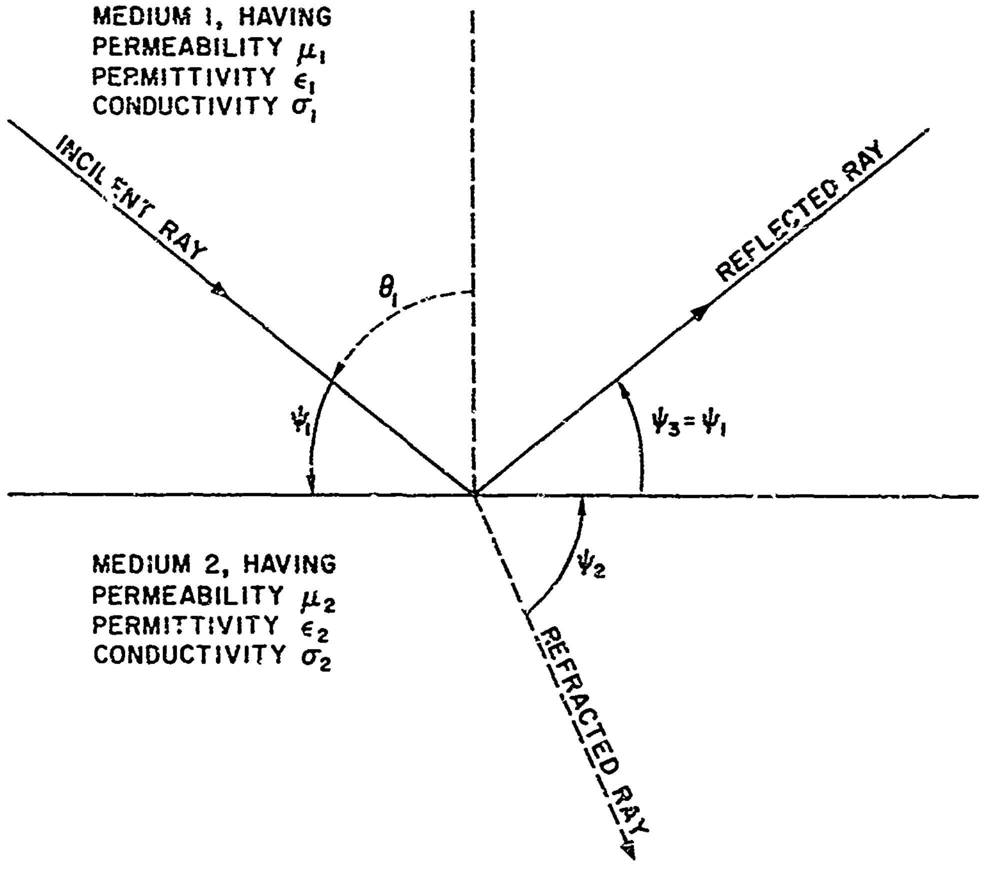

Figure 3. Geometry and definitions for discussion of the reflection coefficient ρ of a wave obliquely incident on the plane interface between two media.

ψ_1 = angle of incidence (in elevation),

ψ_2 = angle of refraction,

ψ_3 = angle of reflection.

[Note: The "optical" angles θ_1, θ_2, θ_3 are the complements of ψ_1, ψ_2, ψ_3, respectively.]

elevation angle ψ_1 measured from the plane itself. (See Fig. 3.) Making the appropriate substitution $\psi_1 = (\pi/2) - \theta_1$, Eqs. (1) and (2) yield Eqs. (67) and (71) in Chapter 3 of Ref. 10.

In Eqs. (1) and (2), the reflection coefficient ρ is the ratio $E_{reflected}/E_{incident}$ of the electric field strength of the reflected wave to that of the incident wave. This is in general a complex quantity, with the reflected wave having always an amplitude less than unity and a phase shift relative to the incident wave. For convenience in computation, this phase shift will always be expressed by denoting a negative phase as a positive phase lag.

If, as is usually the case in antenna work involving ground reflections, μ_1 is equal to μ_2, the equations simplify to:

$$\rho_h = \frac{\sin \psi_1 - \sqrt{\frac{\epsilon_2}{\epsilon_1} - \cos^2 \psi_1}}{\sin \psi_1 + \sqrt{\frac{\epsilon_2}{\epsilon_1} - \cos^2 \psi_1}} , \qquad (3)$$

$$\rho_v = \frac{\frac{\epsilon_2}{\epsilon_1} \sin \psi_1 - \sqrt{\frac{\epsilon_2}{\epsilon_1} - \cos^2 \psi_1}}{\frac{\epsilon_2}{\epsilon_1} \sin \psi_1 + \sqrt{\frac{\epsilon_2}{\epsilon_1} - \cos^2 \psi_1}} . \qquad (4)$$

The permittivity ϵ can be defined as a complex quantity,* to include the effect of loss in the medium. When it is so defined, Eqs. (3) and (4) apply not only to the lossless case but also to the case where one or both media are lossy.

*See, for example, Ref. 11, p. 233 ff.

The properties of ground are ordinarily given in terms of its conductivity σ in mhos/meter, which accounts for its loss, and the dielectric constant (relative permittivity) ϵ_r, which then has only a real part. The real part ϵ' of the complex permittivity is then:

$$\epsilon' = \epsilon_o \epsilon_r \quad , \tag{5}$$

where ϵ_o is the permittivity of free space, 8.854 times 10^{-12} farads/meter. When specified in this manner, ϵ in the Eqs. (3) and (4) should be replaced, with appropriate subscripts, by:

$$\epsilon = \epsilon'\left(1 - j \frac{\sigma}{\omega\epsilon'}\right) \; ; \tag{6}$$

or more simply, by:

$$\epsilon = \epsilon' - j \frac{\sigma}{\omega} \quad . \tag{6a}$$

Here ω is the radio frequency in radians per seond, and the effect of conductance on the dielectric properties is seen to be frequency-dependent.

Usually only medium 2 (the ground) is lossy and the permittivity of medium 1 is equal to that of free space, so that:

$$\epsilon_1 = \epsilon_o \quad . \tag{7}$$

With the complex permittivity of medium 2 denoted by $\left(\epsilon_2' - j \frac{\sigma_2}{\omega}\right)$ and the permittivity of medium 1 by ϵ_o, we can use the definition of the relative complex dielectric constant ϵ_{rc} of medium 2 as:

$$\epsilon_{rc} = \frac{\epsilon_2}{\epsilon_o} \tag{8}$$

$$= \frac{\epsilon_2'}{\epsilon_o} - j\,\frac{\sigma_2}{\omega\epsilon_o} \quad . \tag{8a}$$

Equations (3) and (4) for the reflection coefficients then become:

$$\rho_h = \frac{\sin\psi_1 - \sqrt{\epsilon_{rc} - \cos^2\psi_1}}{\sin\psi_1 + \sqrt{\epsilon_{rc} - \cos^2\psi_1}} \quad , \tag{9}$$

$$\rho_v = \frac{\epsilon_{rc}\sin\psi_1 - \sqrt{\epsilon_{rc} - \cos^2\psi_1}}{\epsilon_{rc}\sin\psi_1 + \sqrt{\epsilon_{rc} - \cos^2\psi_1}} \quad , \tag{10}$$

for the case where only medium 2 is lossy and medium 1 has the permittivity of free space.

For convenience, the part $\frac{\sigma}{\omega\epsilon'}$ of the complex permittivity [see Eq. (6)] is defined by some authors as:

$$a = \frac{\sigma}{\omega\epsilon'} \quad . \tag{11}$$

A small value of "a", much less than 1, indicates that the loss in the dielectric is not appreciable. Very high values of "a", 10^4 and up, indicate that the material is essentially a conductor. The variation of "a" with frequency for various types of terrain is shown in Fig. 4. It is apparent that most types of soil, especially at the higher frequencies, are fairly low-loss dielectrics.

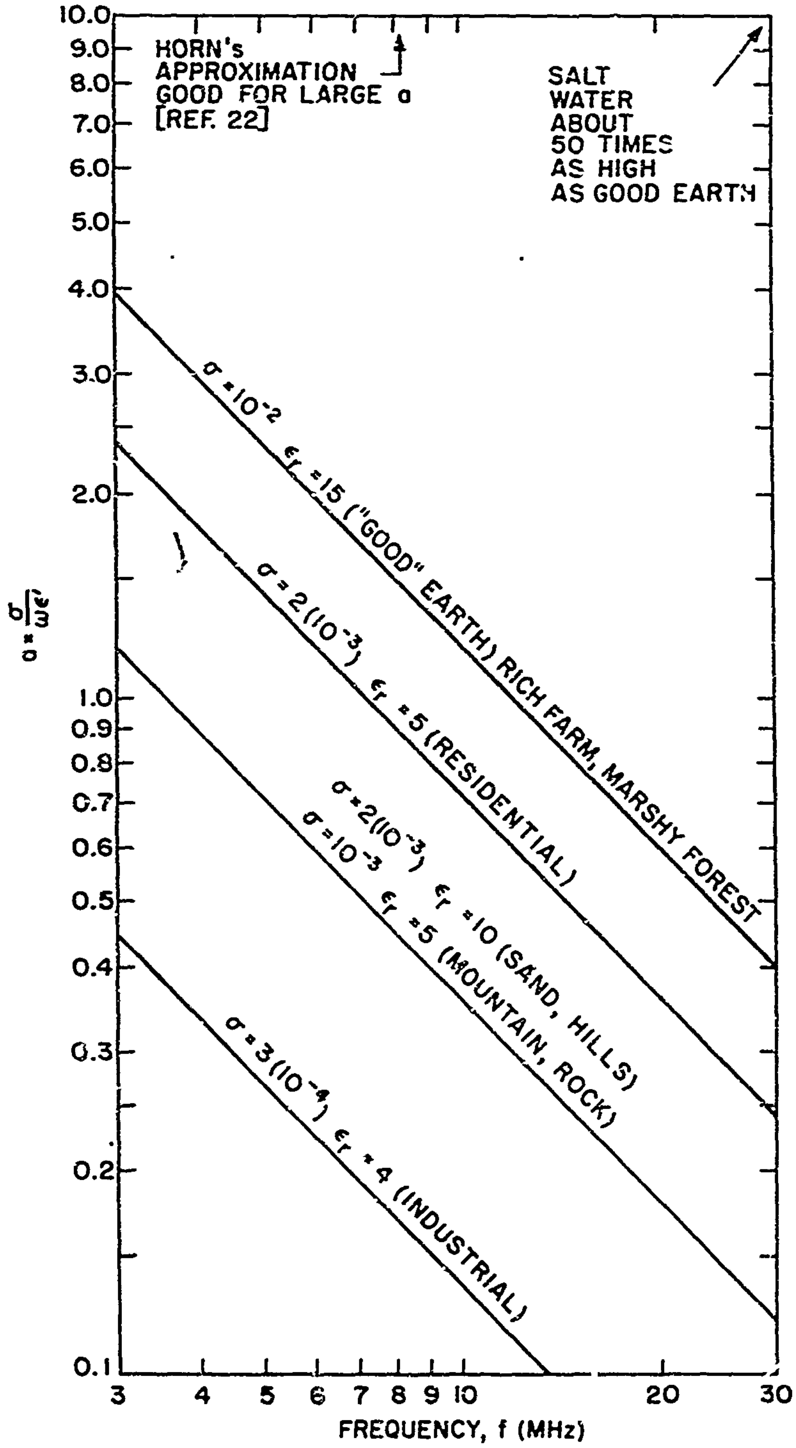

Figure 4. Variation of "a" with frequency for various types of terrain.

Equations (9) and (10) have been programmed for a computer, and curves run for various conditions. Figures 5 and 6 show the reflection coefficient, in amplitude and phase lag, for horizontal and for vertical polarization respectively. The curves are plotted for different values of "a", with the dielectric constant ϵ_r held at 10. It is apparent that there is a great difference between horizontal and vertical polarization. (Note the different scales in Fig. 6 than in Fig. 5.) Also, Figs. 5 and 6 show that for small values of "a" the plots are close together, so that there is little effect on the reflection coefficients until "a" becomes larger than 1. From Fig. 4 it is recalled that for even the most highly conducting ground, "a" is not large compared to 1 over most of the HF range. Therefore, in this range, if an average value of ground conductivity is assumed, and the actual conductivity is somewhat different, the reflection coefficients and the antenna patterns calculated from them will be little affected. The principal exceptions to this occur where the reflecting surface is sea water or where the ground is covered by a conducting screen. (These cases will be discussed in Section K.)

The effect of variation in dielectric constant ϵ_r, over the range of values found in practice, is somewhat greater. Figures 7 and 8 again are for horizontal and for vertical polarization. Here the parameter $\frac{\sigma}{\omega}$ is held constant to bring out the effect of changing ϵ_r. This subject is discussed further in Section E.

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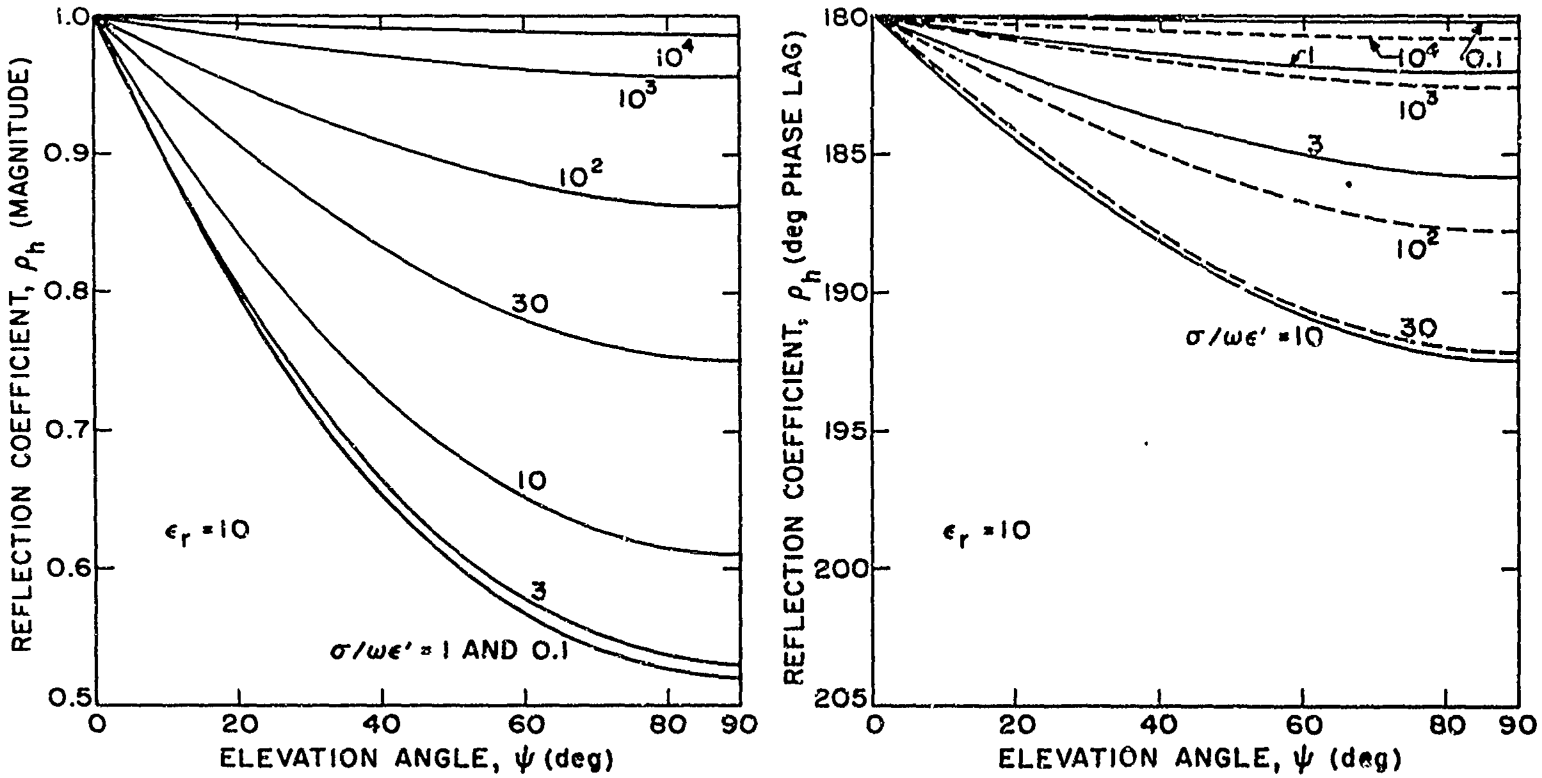


Figure 5. Reflection coefficient $\rho_h \triangleq \frac{E_{reflected}}{E_{incident}}$ for horizontal polarization.

(As a function of $a \triangleq \sigma/\omega\epsilon'$.)

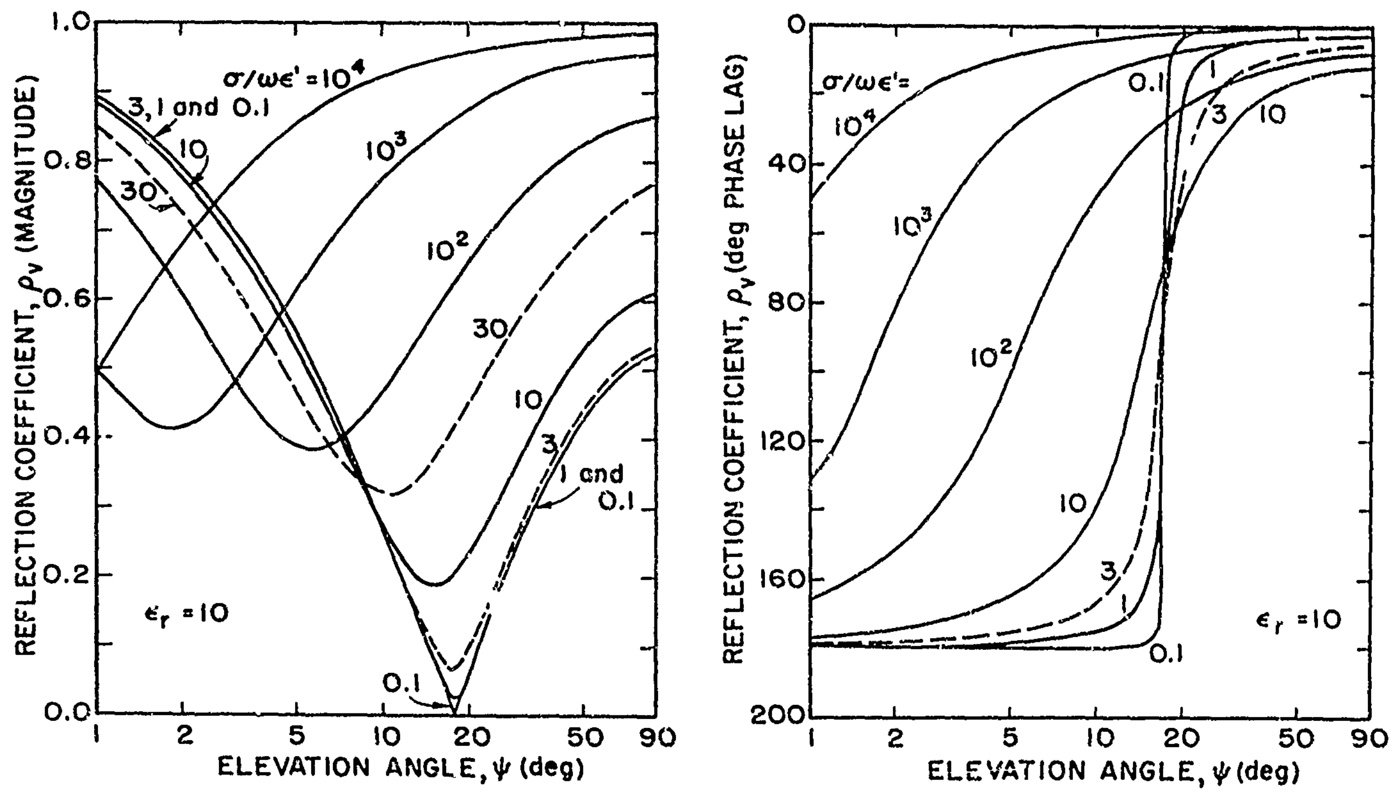


Figure 6. Reflection coefficient $\rho_v \triangleq \frac{E_{reflected}}{E_{incident}}$ for vertical polarization.

(As a function of $a \triangleq \sigma/\omega\epsilon'$.)

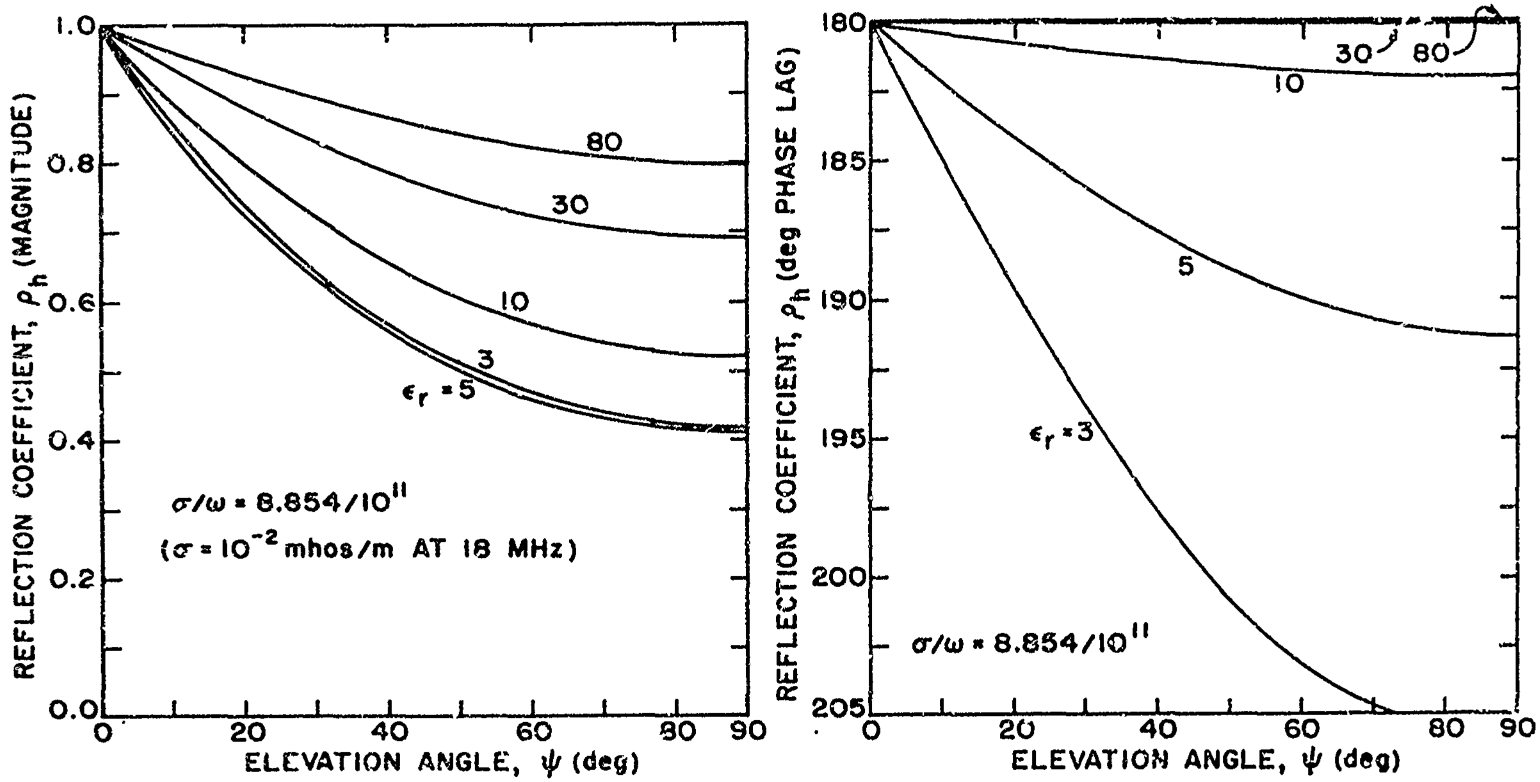


Figure 7. Reflection coefficient ρ_h for horizontal polarizati.n.

(As a function of ϵ_r.)

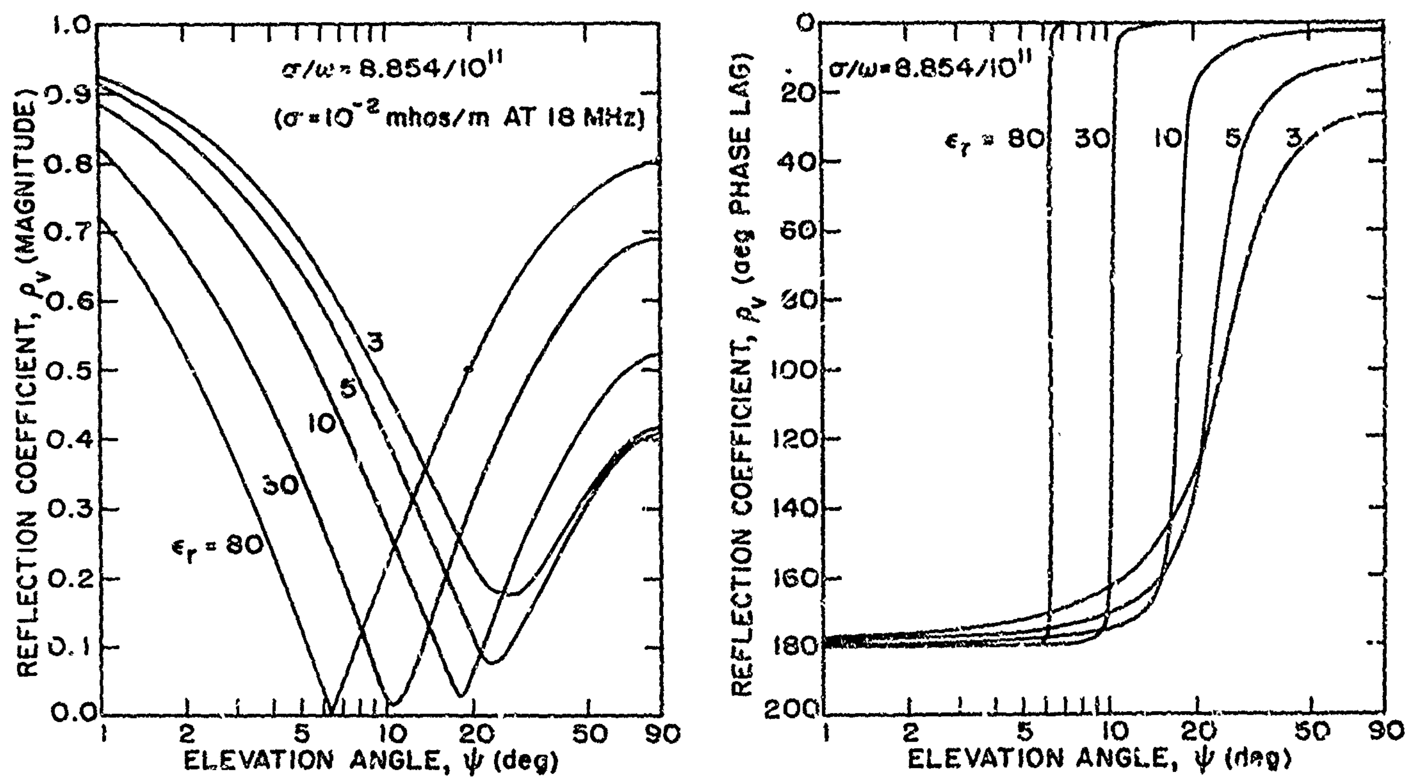


Figure 8. Reflection coefficient ρ_v for vertical polarization.

(As a function of ϵ_r.)

D. THE EFFECT OF THE REFLECTION COEFFICIENTS ON ELEVATION-ANGLE PATTERNS OF HORIZONTAL AND VERTICAL ANTENNAS

The elevation-angle directivity pattern of a simple antenna over actual ground is computed in the usual manner, by vectorially adding the direct signal to the ground-reflected signal, assumed to originate at an image antenna below the reflecting surface by a distance equal to the actual antenna height. Referring to Figs. 5-8, the amplitude of the reflected wave is not the same as that of the incident wave, but is less in proportion to the magnitude of the reflection coefficient found by Eqs. (9) or (10) for the particular polarization and ground constants and as a function of the elevation angle ψ_1. Likewise, the phase lag occurring at reflection is minus the phase angle of the reflection coefficient obtained by solving Eq. (9) or Eq. (10) respectively.

Note that for vertical polarization, at the elevation angle (the "Brewster angle"*) for which the phase lag at reflection is 90 deg, the amplitude of the reflected wave is a minimum. In the HF range and for the usual types of ground, the Brewster angle is in the region of 15 to 18 deg elevation. As the elevation angle becomes low compared to the Brewster angle, the reflection coefficient for vertical polarization approaches that for horizontal polarization, and the ground reflection behavior predicted by the perfectly-conducting-ground approximation is no longer obtained. When the incident wave has both horizontally and vertically polarized components, they must be calculated separately because of the different reflection coefficients which apply. For average

*More properly referred to as the "pseudo-Brewster" angle when the minimum amplitude of the reflected wave is not small, say greater than 0.1 of the incident wave amplitude.

ground and in the HF range, the reflection coefficients may be taken from the most closely applicable curves of Figs. 5 and 6, or of Figs. 7 and 8. Once the reflection coefficients have been obtained, the pattern calculations can be done manually. If a large number of patterns are to be made, it will be found helpful to use a computer.

E. THE DESIGN APPROACH FOR MATCHING THE AMPLITUDE PATTERNS OF THE UNEQUAL-HEIGHT CROSSED ANTENNA PAIR

The object in designing the antenna pair that is the subject of this report was to obtain at a reasonable cost horizontally and vertically polarized elevation-angle directivity patterns that would be as much alike as possible and would cover the frequency range 13 to 26 MHz with elevation angles from 25 deg down to as low as feasible. Also, if an antenna pair could be designed which did not need a ground screen, there would be obvious advantages in reducing the requirement for real-estate acquisition, the expense of ground screen materials and installation, and in the availability of the land for agricultural and grazing purposes.

The antennas were conceived of as mounted at different heights in order to compensate for the different reflecting properties of average ground for vertically and horizontally polarized incident waves. In the resulting design, the heights were chosen to place the first (major) elevation lobes of the two antennas to cover about 12 deg to 26 deg at 17 MHz (with somewhat higher angle coverage at lower frequencies and vice versa), and to make these elevation lobes coincide as nearly as possible for horizontal and vertical polarizations.

Elevation patterns were first computed for a short horizontal dipole and a short vertical dipole at a height of one wavelength (1λ) over flat terrain having ground constants $\epsilon_r = 10$ and $a = 3$. Assumptions included (1) that the horizontal antenna free-space pattern is non-directional in elevation, and (2) that the vertical antenna directivity in free space is proportional to the cosine of the angle of elevation. Figure 9 shows the resulting computed amplitude patterns.

It is seen that the main (lowest) lobe of the horizontal antenna has a simple pattern with a large maximum, because of the large amplitude and nearly constant phase of the reflected wave at elevation angles below 30 deg (see Fig. 5). For the vertical antenna, the nose of the main lobe is

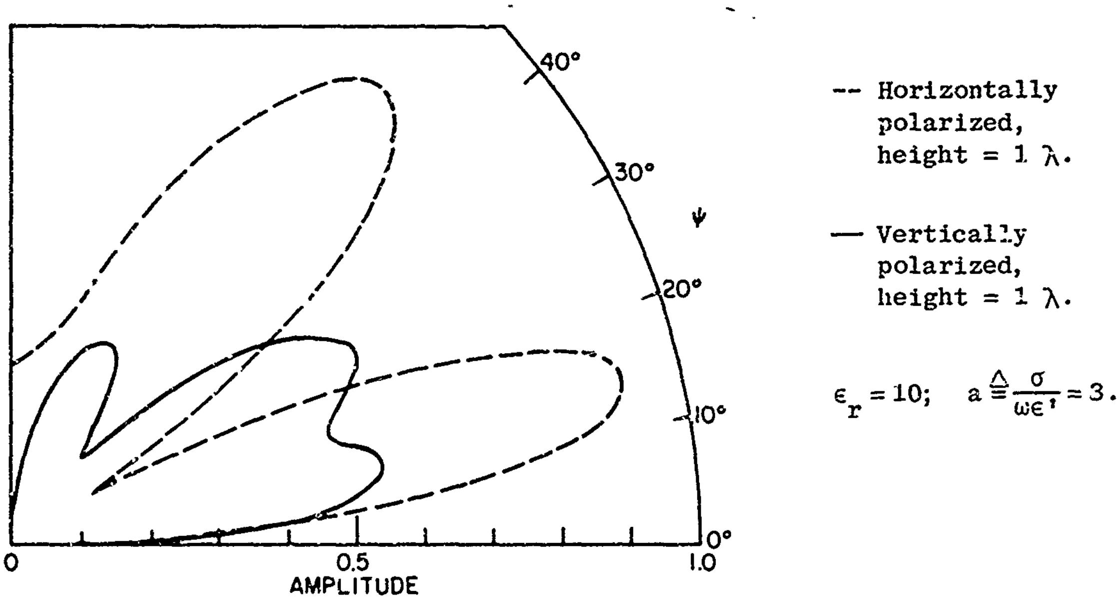
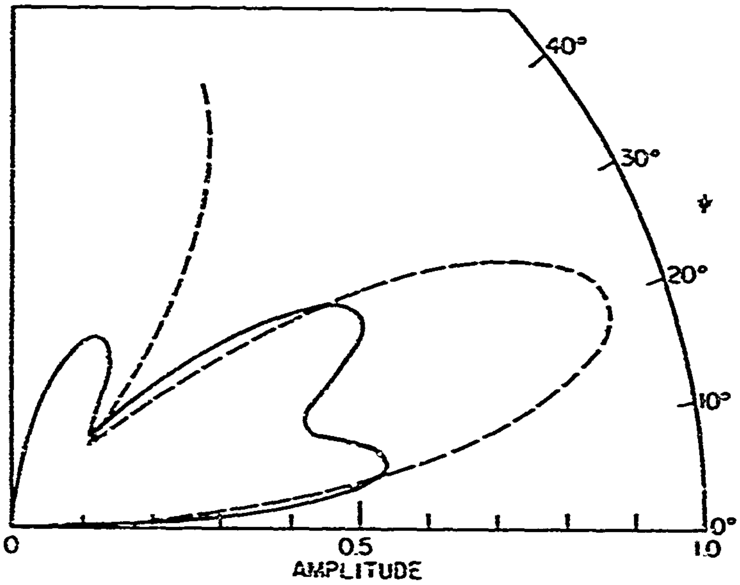


Figure 9. Computed elevation patterns of equal-height, crossed short dipoles over "good" ground.

indented at around 17 deg elevation, its maximum amplitude is much less than that of the horizontal antenna, and the first null is at a considerably higher angle. This is caused (as shown in Fig. 6) by the rapid change of phase of the reflected wave, nearly 180 deg between elevation angles of 5 deg and 30 deg, and the fact that its amplitude decreases to a minimum near an elevation angle of 17 deg (the Brewster angle) as the phase of the reflected wave passes through 90 deg.

By trial and error, the height of the horizontal antenna was dropped to 0.71 wavelength to make the first null in its elevation pattern coincide with that of the vertical antenna. The patterns of Fig. 10 resulted. These show as good a coincidence as possible between the major lobes of the two patterns. The coincidence remains good down to quite low angles, though of course the radiation efficiency of both antennas declines. The heights of 1 and 0.71 wavelength at the lowest desired frequency (13 MHz) are equivalent to physical heights of 76 ft for the vertical array and 54 ft for the horizontal array.

With these physical heights, patterns were computed for 17 and 22 MHz, shown in Figs. 11 and 12. Quite a good match between the main lobes is maintained over this frequency range; it is poorer at 28 MHz but still usable (see Fig. 13). The match is also maintained to lower electrical heights than 1 λ/0.71 λ (see Fig. 14 for 10 MHz); but the performances of the antennas at the lower elevation angles (which were of principal interest) begin to suffer. Accordingly, the physical heights of 76 ft (vertical antenna) and 54 ft (horizontal antenna) were adopted as a compromise--giving good pattern coincidence at lower frequencies, and good low-angle coverage at the higher end of the HF band, while maintaining a reasonable height for the supporting structure.



— Horizontally polarized, height = 54 ft (0.71 λ).

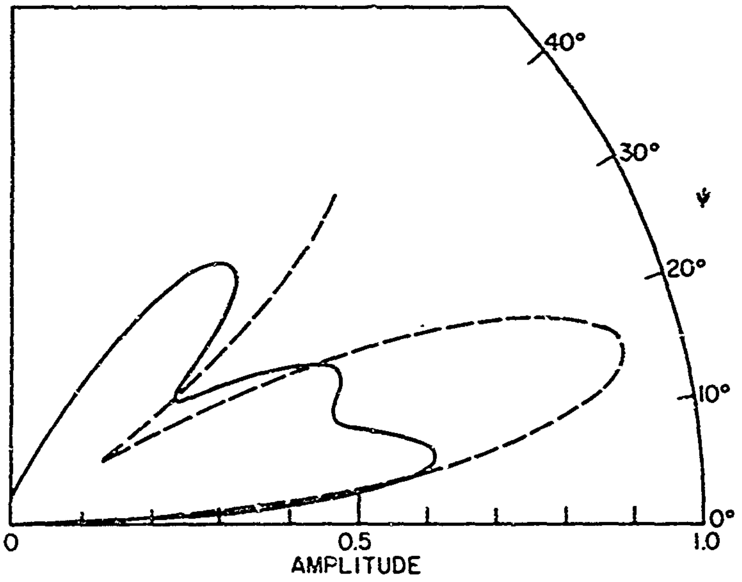
— Vertically polarized, height = 76 ft (1.0 λ).

$\epsilon_r = 10$; $\sigma = 10^{-2}$ mhos/m;

a = 1.4.

Figure 10. Computed elevation patterns of unequal-height, crossed short dipoles over "good" ground.

f = 13 MHz.



-- Horizontally polarized, height = 54 ft (0.93 λ).

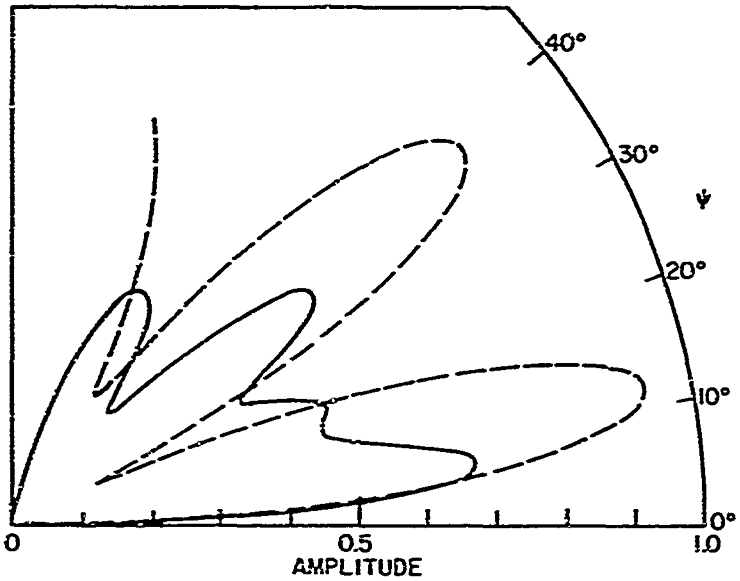
— Vertically polarized, height = 76 ft (1.31 λ).

$\epsilon_r = 10$; $\sigma = 10^{-2}$ mhos/m;

a = 1.1.

Figure 11. Computed elevation patterns of unequal-height, crossed short dipoles over "good" ground.

f = 17 MHz.



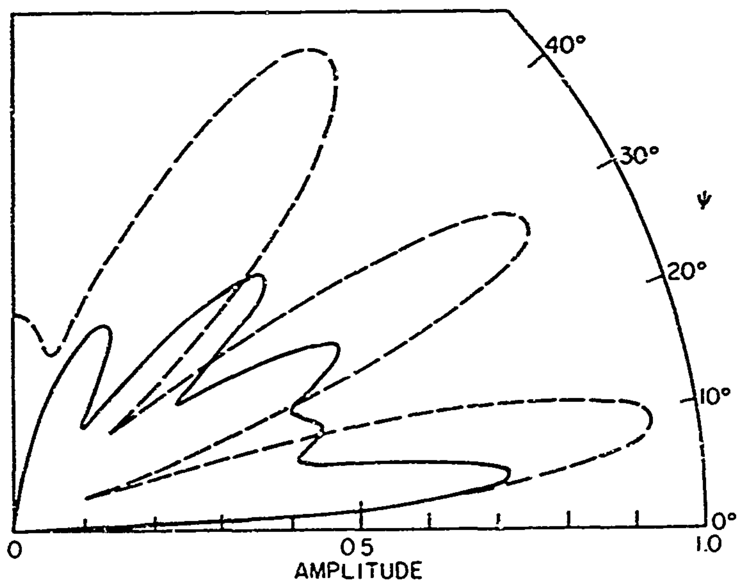
-- Horizontally polarized, height = 54 ft (1.21 λ).

— Vertically polarized, height = 76 ft (1.70 λ).

$\epsilon_r = 10$; $\sigma = 10^{-2}$ mhos/m; $a = 0.8$.

Figure 12. Computed elevation patterns of unequal-height, crossed short dipoles over "good" ground.

f = 22 MHz.



-- Horizontally polarized, height = 54 ft (1.54 λ).

— Vertically polarized, height = 76 ft (2.16 λ).

$\epsilon_r = 10$; $\sigma = 10^{-2}$ mhos/m; $a = 0.65$.

Figure 13. Computed elevation patterns of unequal-height, crossed short dipoles over "good" ground.

f = 28 MHz.

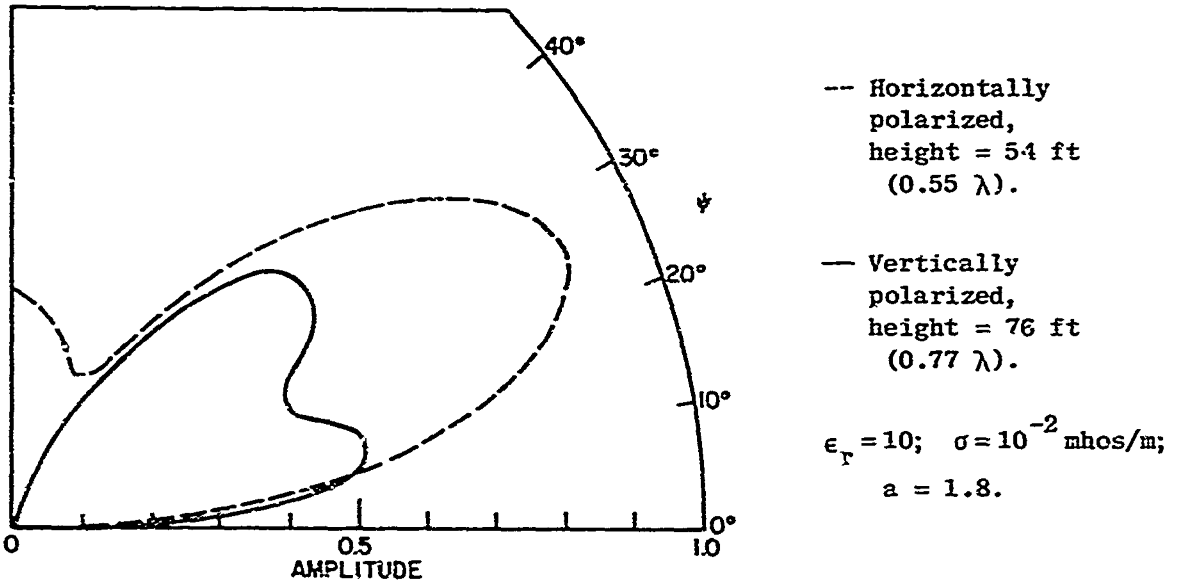


Figure 14. Computed elevation patterns of unequal-height, crossed short dipoles over "good" ground.

f = 10 MHz.

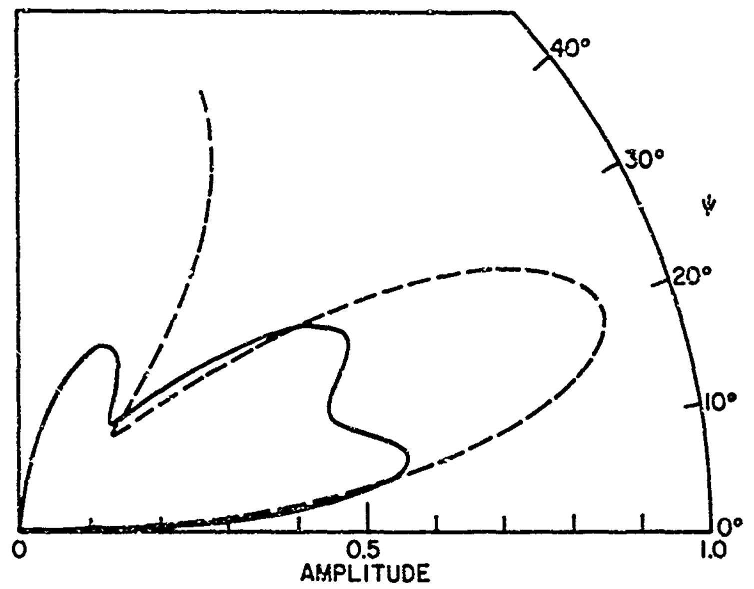
Thus far the approach is quite general; it is applicable to any type of antenna which gives linear polarization, is operable independently of ground connections, and has the bandwidth necessary for the application. Biconical dipoles were originally considered. However, horizontally polarized log-periodic antennas covering the desired frequency range and having moderate directivity were already available at SEL. Based on this experience it was decided to try to adapt them to the cross-polarized application.

These antennas were erected at heights of 76 ft (vertical array) and 54 ft (horizontal array), so that the elevation patterns of Figs. 10-13 (frequencies 13 MHz to 28 MHz) apply to them. (The intended antenna frequency coverage does not include 10 MHz, the frequency of Fig. 14.) The free-space directive patterns of the LPA's are not included in Figs. 10-13; but the main beam of this type antenna, in both the vertical and horizontal planes, is broad enough (over ±30 deg) that the shapes of the main lobes in Figs. 10-13 are not greatly modified by the free-space directionality of the antennas.

The patterns of Figs. 10-14 were obtained assuming a constant "high" value of ground conductivity ($\sigma = 10^{-2}$ mhos/m) and a dielectric constant $\epsilon_r = 10$. These characteristics relate to what has been called "good ground." As previously shown, the effect of variation in conductivity in the normal range is small (see Figs. 5-6); but variation of ϵ_r in the range normally encountered needs further consideration. Figure 15 shows sample plots of the calculated elevation patterns of the antennas over ground having $\epsilon_r = 15$ and $\epsilon_r = 5$, while the conductivity, $\sigma = 10^{-3}$ mhos/m, is so low as to be insignificant. It is seen that, while there is a noticeable difference in the pattern shapes (especially the vertical) between $\epsilon_r = 5$ and $\epsilon_r = 15$, the matching between the horizontal and vertical elevation patterns holds quite well.

For many purposes it is sufficient to know the amplitude relationship between the horizontal and vertical components of the signals radiated or received by the antennas. For other uses, such as circular polarization, it is also desirable that these components be as nearly equal as possible.

The computed amplitude relationship between the signals radiated by the horizontal and vertical antennas over "good" ground is plotted directly in Fig. 16, for the same conditions as Figs. 10-13. It is shown that the amplitude relationship is a function of both elevation angle and frequency; the horizontal antenna tends to radiate more effectively at intermediate

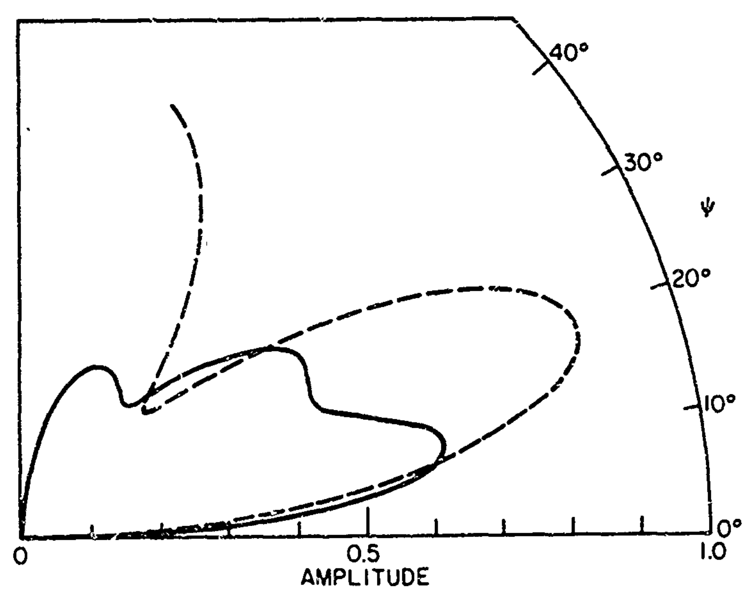


(a)

ϵ_r = 15;

$\sigma = 10^{-3}$ mhos/m;

a = 0.09.



(b)

ϵ_r = 5;

$\sigma = 10^{-3}$ mhos/m,

a = 0.28.

Figure 15. Effect of dielectric constant ϵ_r on computed elevation patterns of unequal-height, crossed short dipoles.

f = 13 MHz.

-- Horizontally polarized, height = 54 ft (0.71 λ).

— Vertically polarized, height = 76 ft (1.0 λ).

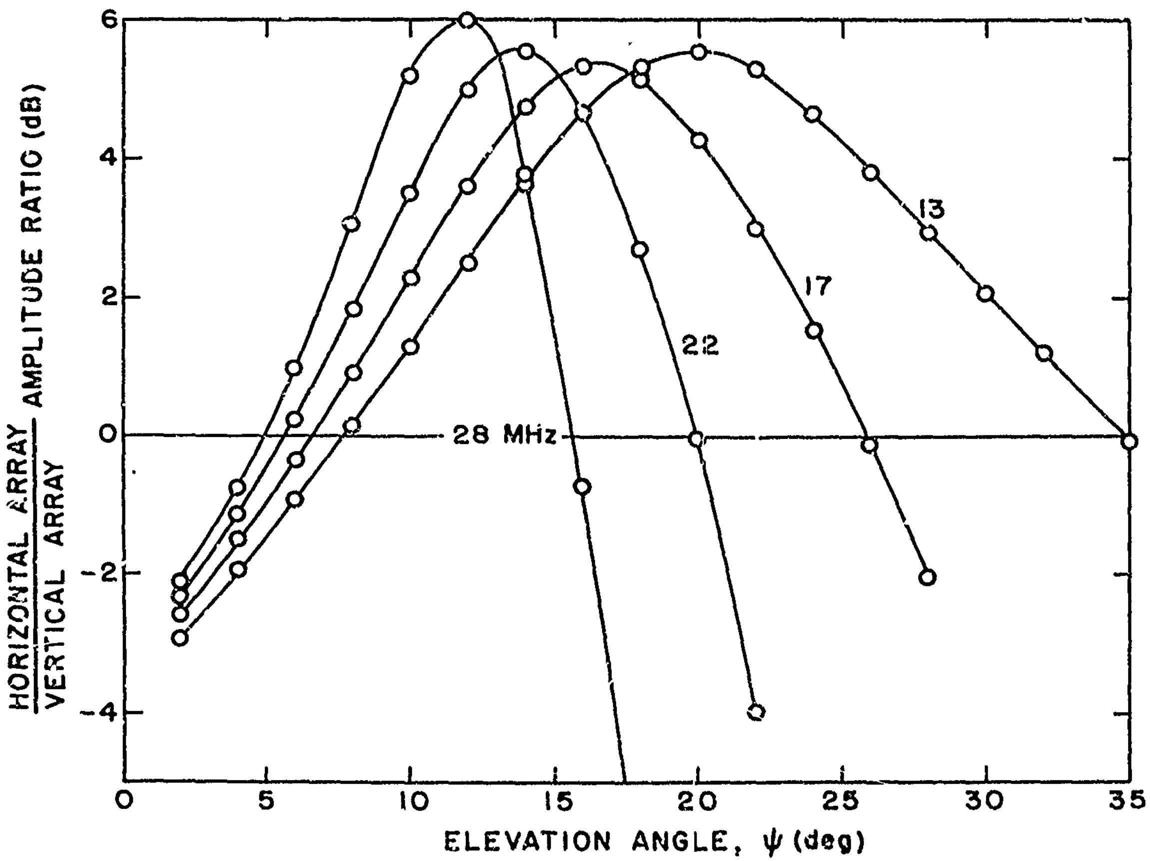


Figure 16. Computed amplitude ratio, horizontally polarized to vertically polarized signal, as a function of elevation angle and frequency.

(Over "good" ground: $\epsilon_r = 10$, $\sigma = 10^{-2}$ mhos/m.)

angles, above 10 deg; while at the lowest angles the vertical antenna has a slight advantage. At angles over 15 deg, the possible advantage of the vertical antenna is very much a function of frequency.

If the elevation angle and frequency at which it is desired to optimize the amplitude relationship between the horizontally and vertically polarized components can be specified, Fig. 16 may be used to determine the size of an attenuating pad to be inserted in the feed line to the horizontal or vertical antenna as required. This possibility is discussed further in Section IV, Experimental Results, Subsection A. It may be noted here, however, that experience so far tends to show that the difference between horizontal and vertical antenna gains is only about half as much as predicted by Fig. 16, and that a 2 dB pad inserted in the horizontal feed line, or no pad at all, are reasonable compromises for general use.

F. PHASE RELATIONSHIP BETWEEN HORIZONTAL AND VERTICAL RADIATED SIGNALS

The computer runs which produced Figs. 9 through 15 also yielded the phase of the resultant radiated wave--that is, the sum of the ground-reflected and directly radiated waves--relative to the phase of the direct wave, as a function of elevation angle. Considering only the effect of ground reflection, the phase difference between the resultant horizontally and vertically polarized radiated signals tends to be zero at about the center of the major elevation lobe. Their phases do not change at the same rate across the lobe; Fig. 17 shows this component of phase lag of the signal from the horizontally polarized antenna with respect to that from the vertically polarized one.

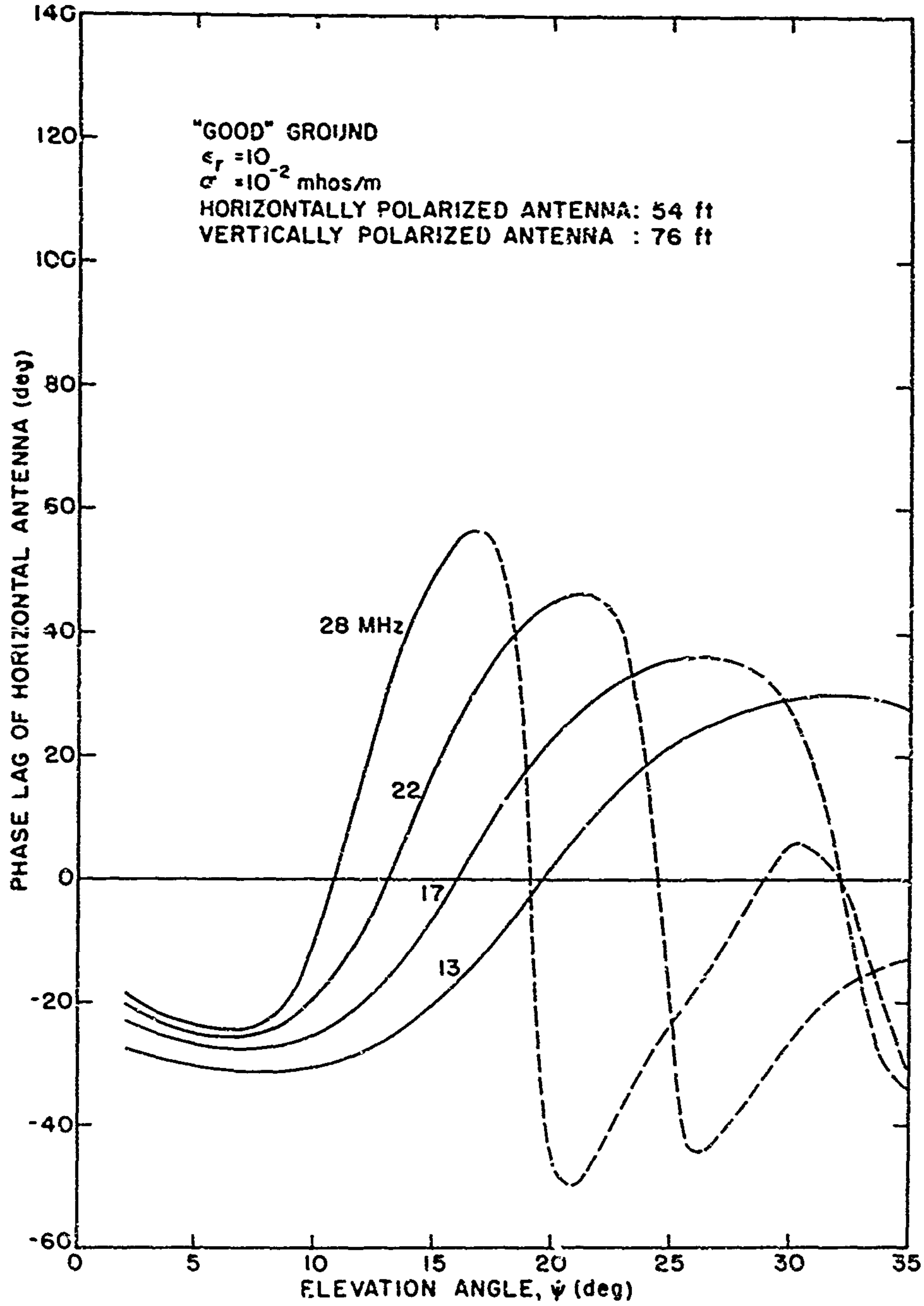


Figure 17. Phase lag of radiated signal from horizontally polarized antenna relative to that from vertically polarized antenna, OMITTING the lag due to difference in antenna height.

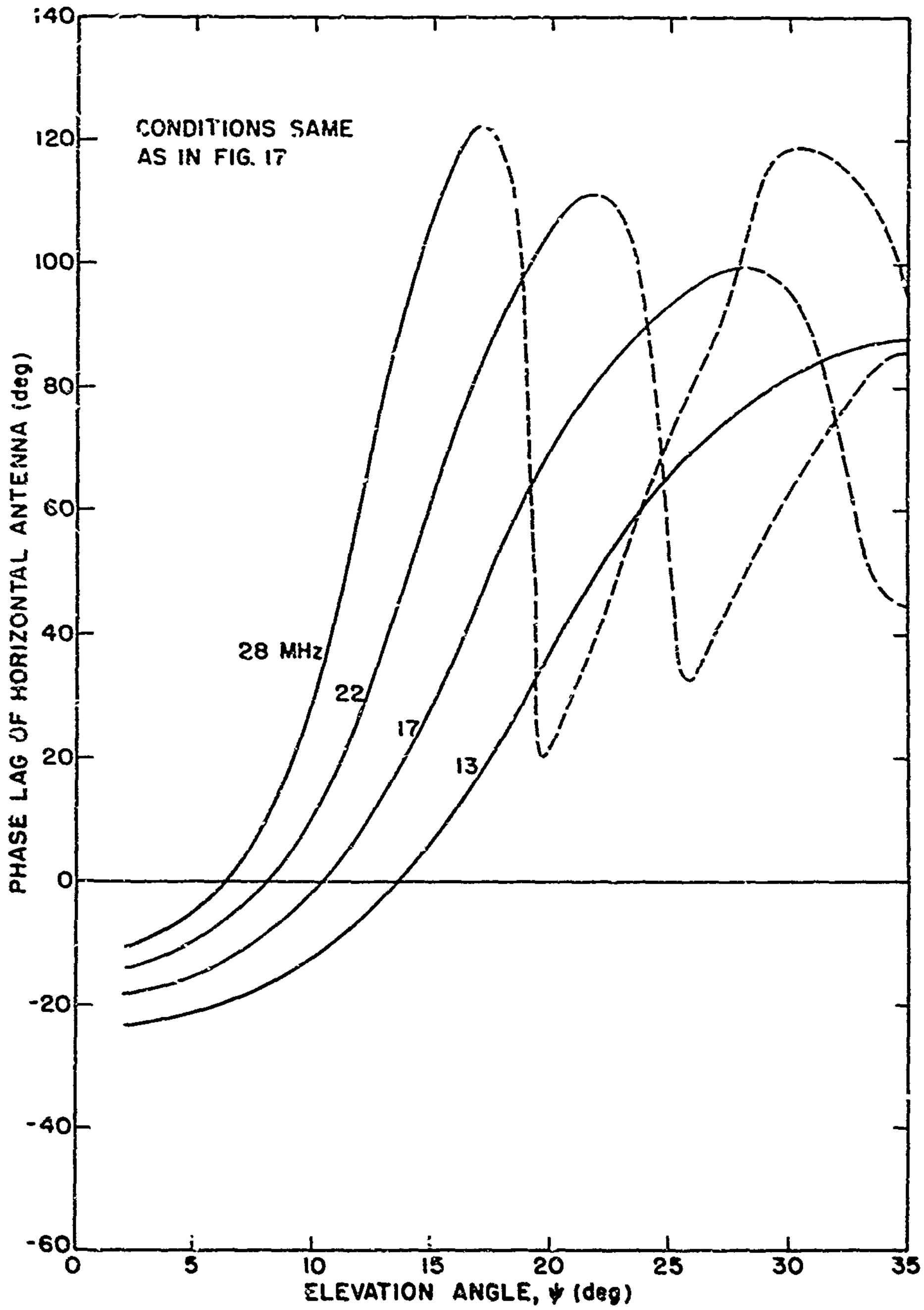


Figure 18. Phase lag of radiated signal from horizontally polarized antenna relative to that from vertically polarized antenna, INCLUDING the lag due to difference in antenna height.

There is an additional phase lag in the signal from the horizontal antenna, due to the difference in height between the antennas and proportional to the sine of the angle of elevation. The total phase difference including this term is plotted in Fig. 18, for "good" ground.

If the two antennas are to be used together to form a circularly polarized array, it is necessary that the signals radiated by the two antennas not only be of equal amplitude, but also be in quadrature phase relationship at the chosen frequency and elevation angle [Ref. 7]. It would appear from Fig. 18 that with a single phasing element such as a length of coaxial cable, quadrature phase cannot be maintained over a wide range of frequencies and elevation angles. The phasing element must in general be chosen for a particular frequency and elevation angle, though, as will be seen, it is possible to balance the various factors to some extent to maintain the phase difference acceptably near quadrature over a range of frequencies.

G. PHASING FOR CIRCULAR POLARIZATION BY A LENGTH OF CABLE

The simplest way to obtain the quadrature phasing is to insert a suitable length of cable in series with one of the two antenna feed lines (which otherwise are carefully made equal in electrical length). The first experiments using circular polarization were done using the length of cable in the feedline to the horizontal antenna.

It was observed later, however, that putting the phasing cable in the vertical antenna feed line would tend to keep the phase difference near quadrature over a wider frequency range. Figure 19 shows the physical length of extra cable needed to obtain quadrature phase at various

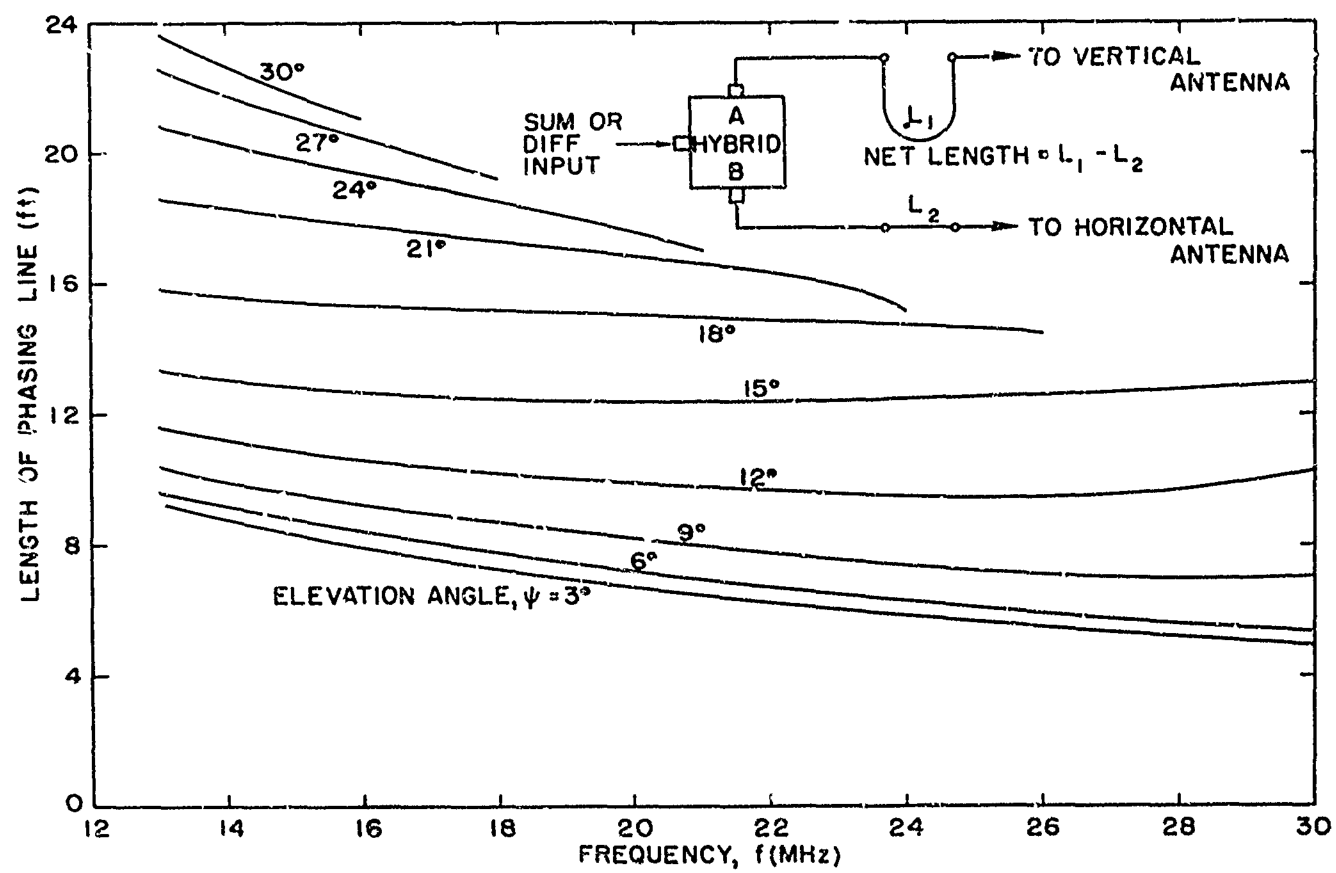


Figure 19. Length of quadrature phasing line versus frequency for various elevation angles. (Phasing line in series with vertical feedline.)

$\epsilon_r = 10$; $\sigma = 10^{-2}$ mhos/m; velocity factor of line = 0.659.

Horizontally polarized antenna 54 ft high.

Vertically polarized antenna 76 ft high.

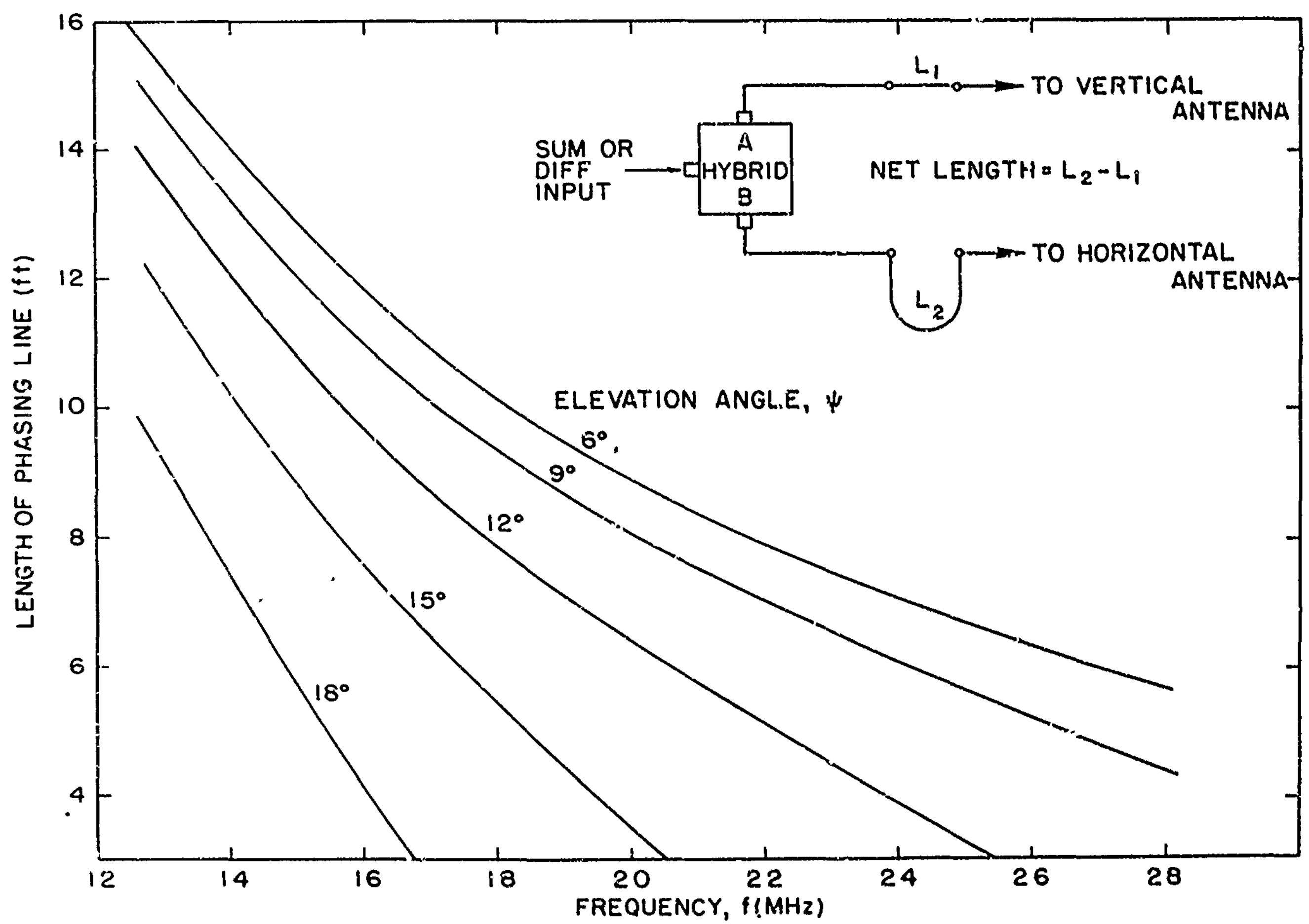


Figure 20. Length of quadrature phasing line versus frequency for various elevation angles. (Phasing line in series with horizontal feedline.)

$\epsilon_r = 10$; $\sigma = 10^{-2}$ mhos/m; velocity factor of line = 0.659.
Horizontally polarized antenna 54 ft high.
Vertically polarized antenna 76 ft high.

elevation angles as a function of frequency, over "good" ground. The velocity of propagation in the phasing cable is assumed to be 65.9 per cent, which applies to all the usual 50 ohm polyethylene cables such as RG-17A/U and RG-8A/U, though not to foam dielectric or teflon cable.

The curves in Fig. 19 were discontinued where they began to curve abruptly, that is, where the elevation angle at a given frequency began to approach the first null above the major lobe of the elevation-angle amplitude pattern. At greater elevation angles the phase difference between the horizontal and vertical radiated fields (shown by the dotted lines in Figs. 17 and 18) changes much more rapidly.

Within the range of the curves of Fig. 19, for any chosen elevation angle the curve of cable length vs frequency tends to be fairly near horizontal, so that for any one elevation angle between about 12 and 18 deg, a phasing line length can be selected which will give nearly the correct phase over a large part of the frequency range. At lower and higher angles the phase variation over the frequency range is larger but still reasonable. At a given point the error angle φ in degrees by which the phase between the horizontally and vertically polarized signals departs from the desired quadrature value due to an incorrect cable length is

$$\varphi = 0.555\, f_{MHz}\, \ell_e \quad , \tag{12}$$

where f_{MHz} = frequency in MHz and ℓ_e = cable length error in feet.

For comparison, Fig. 20 shows the cable length required to obtain quadrature phasing when the phasing cable is inserted in the horizontal antenna feed line. The required length of cable for a given elevation angle and frequency is generally shorter, but the departure from correct phase with change of frequency is much more rapid.

H. DETERMINATION OF THE ANGLE OF ELEVATION

It remains to be determined what the correct angle of elevation is in a given situation, so that Fig. 19 can be used to find the length of phasing cable for circular polarization. The path length should be known, as well as whether E-layer or F2-layer propagation is likely to prevail. For single-hop distances (less than about 2000 km for E-layer and 4000 km for F-layer reflection) where the virtual height of the reflecting layer is known at least approximately, the elevation angle may be found from Fig. 21, or by use of the "Skywave Transmission Chart" by Prof. R. A. Helliwell [Ref. 14].

The height of the E layer (either the normal daytime E or sporadic E) is fairly constant at about 110 km. The F2 layer height is quite variable, being affected by the time of day, the season, the solar activity and sunspot cycle, the frequency, and the latitude. The height ranges from 250 to 450 km. Discussion of these variations and of the multi-hop situation is beyond the scope of this report. For a first rough approximation the F2-layer height may be taken as 325 km during the day, dropping to 275 km at night. More detailed information is contained in Refs. 15, 16 and 17.

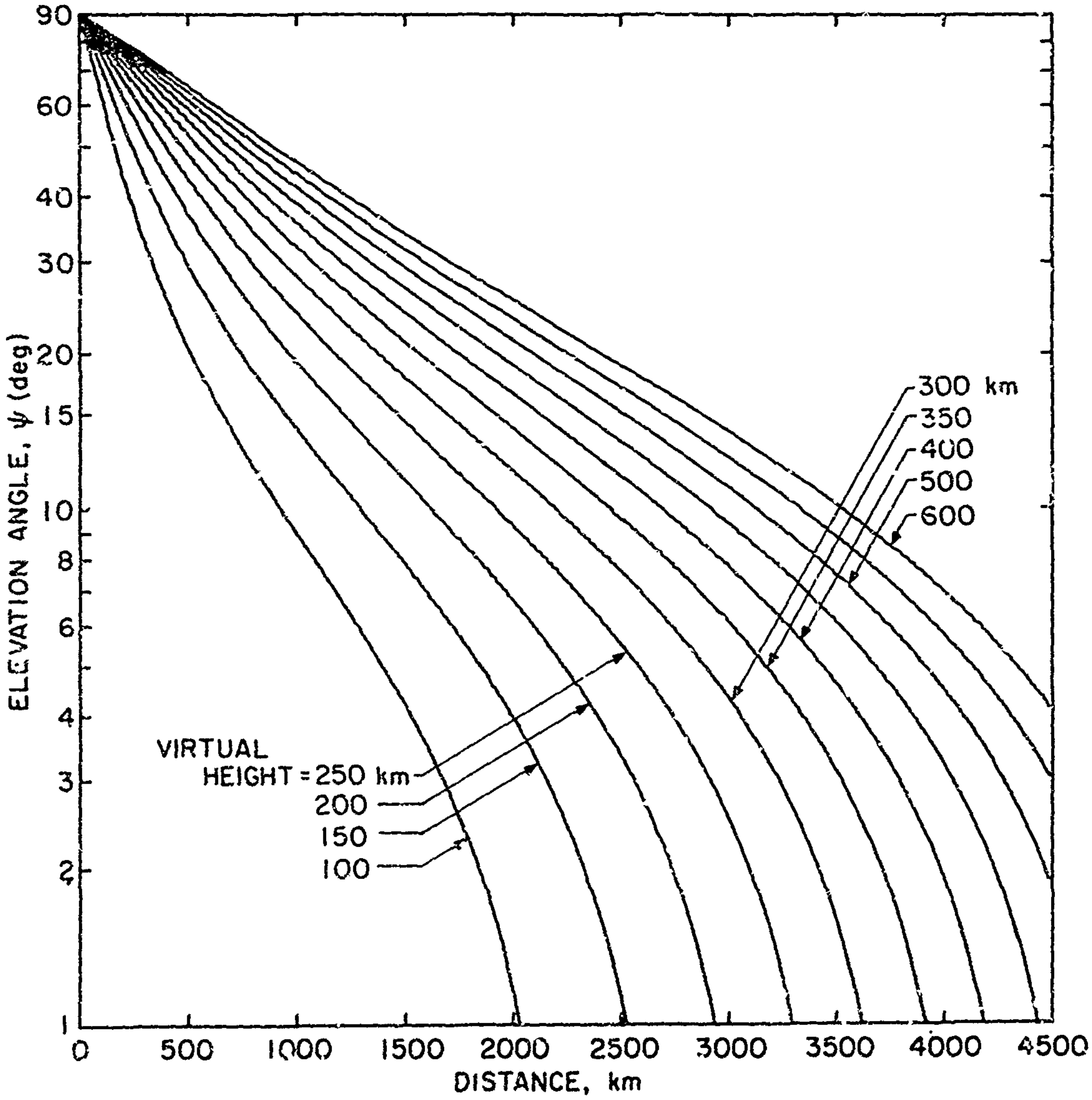


Figure 21. Elevation angle computed from simple one-hop geometry.

I. AZIMUTHAL COVERAGE OF THE CROSS-POLARIZED ANTENNA

In the case of the cross-polarized LPA array which has been discussed so far, pure horizontal polarization is only available along the azimuthal axis of the array. At azimuth angles off the axis the horizontal antenna output contains an increasing amount of vertical polarization. At 90 deg from the axis there is an essentially complete null for horizontal polarization, so that all the radiated energy is vertically polarized. This means in practice that the antennas should be pointed as exactly as possible in the desired azimuthal direction of propagation, or at least within ± 20 deg of it, in order to obtain good purity of the horizontally polarized output or good circularity in the circularly polarized outputs. If wider azimuth coverage is needed, it will be necessary to use antennas which individually have the necessary azimuth coverage and which maintain essentially pure horizontal or vertical polarization over the azimuth sector. If these antennas are of types whose radiated phase is a function of azimuth angle, such as turnstiles, care must be taken that the phases of the horizontal and vertical arrays vary with azimuth in exactly the same manner.

One interesting possibility would be a single vertical coaxial dipole, with a small horizontal loop antenna at a height 0.71 of the height to the center of the vertical antenna. The horizontal loop would have to be small enough so that its circumference is short in terms of wavelength; thus the radiated signal phase would be essentially independent of azimuth. Such an arrangement could provide circular polarization at all azimuths. The low impedance of the loop and the variation of its impedance with frequency would tend to make this a narrow-band device for transmitting.

For receiving applications, an untuned balanced loop, combined with a preamplifier circuit having complementary frequency response over the 2 to 32 MHz range, is made by EMI Electronics Canada Ltd. and used in their Model 8E13 and related types of arrays. It would appear that the combination of one of these loops mounted horizontally, with a coaxial vertical dipole broadbanded by the usual methods and mounted above it, would provide omnidirectional coverage and circular polarization over a wide frequency range. (The overall phase characteristic of the loop and preamplifier would have to be considered, however.) A combination of a horizontally mounted loop with a vertically mounted loop above it would also be useful, though cross-polarized patterns would only be obtained in the plane of the vertical loop. In either case it should be possible to drop the feedlines of both antennas straight down the supporting pole without any problems.

J. PHASING FOR CIRCULAR POLARIZATION BY LUMPED-CONSTANT NETWORKS

It can be seen from Fig. 19 that for any selected length of phasing cable in the vertical antenna lead, the elevation angle corresponding to quadrature phasing tends to rise with frequency. This is especially true outside the 12 to 18 deg range. This is not altogether a bad thing, since the virtual height of the reflecting layer in the ionosphere also tends to rise as the frequency is increased toward the maximum usable frequency (MUF). Thus a chosen length of phasing line might give a better approximation to the phase for circular polarization over a given path than Fig. 19 would imply. The correspondence is not exact, however; the rise in virtual height with frequency under a given set of conditions is more rapid as the MUF is approached, while the greatest downward slope of the curves in Fig. 19 tends to occur over the lower part of the frequency range.

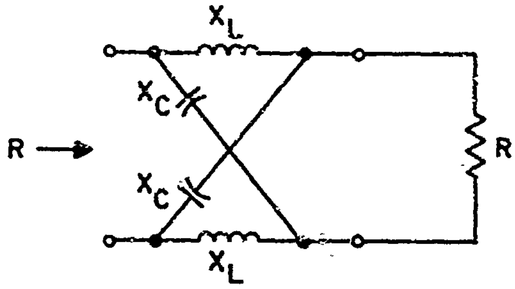
It is well known that pairs of lumped-element phase networks can be found, which will approximate any continuous curve of phase difference vs frequency as closely as desired [Refs. 18, 19]. It should therefore be possible to obtain a closer approximation to the desired curve than is afforded by the curves of Fig. 19, by the use of a properly designed pair of lumped-element phase networks in the horizontal and vertical feedlines, or by a combination of such networks with a coaxial-cable phasing line. For the present application, the phasing networks should be virtually lossless, containing only reactances and transformers. Examples of usable phasing sections are shown in Fig. 22.

Considering the number of approximations in the theory, the use of such lumped-constant networks to obtain better phase compensation than that of Fig. 19 would hardly be justified unless some means of actually measuring the circularity of the radiated patterns could be implemented.

K. OPERATION OVER WATER OR GROUND SCREEN

The particular arrangement of cross-polarized antennas which has been described is intended for operation over ordinary ground. It has been shown that the matching achieved between the horizontal and vertical elevation patterns in phase and amplitude is not very critical with respect to the parameters of the ground within their usual range.

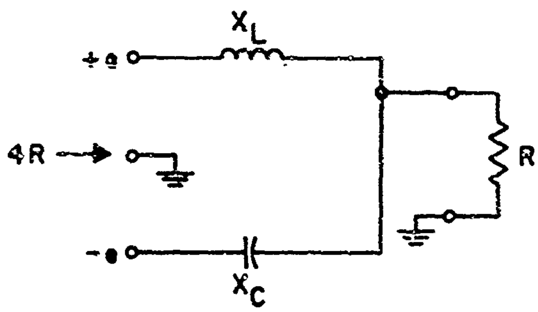
It might occur, however, that the available land is already covered with ground screen, or that the ground is quite irregular so that the



Phase shift $\beta = 2 \arctan f/f_o$.

At f_o, $X_L = X_C = R$.

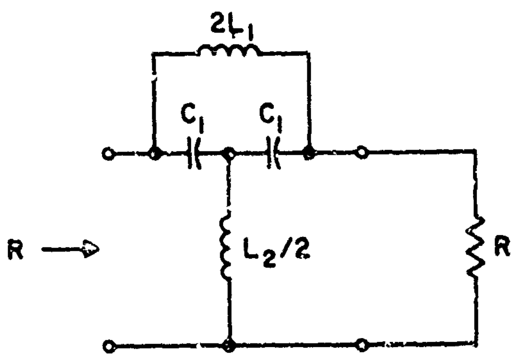
(a) LC full lattice.



Phase shift $\beta = 2 \arctan f/f_o$.

At f_o, $X_L = X_C = 2R$.

(b) LC half lattice.



Phase shift $\beta = 2 \arctan \dfrac{f/f_o}{1 - \left(\dfrac{f}{f_o}\right)^2}$

$L_1 = \dfrac{R}{2\pi}$,

$L_2 = R^2 C_1$,

$C_1 = \dfrac{1}{2\pi R f_o^2}$.

(c) LC bridged-T.

Note: This network is a special case of the network of Fig. 17-21(b) in Reference 19.

Figure 22. Lossless phase-shift network sections.

installation of ground screen would be considered in order to obtain a more uniform reflecting surface. Or, it might be desired to operate with fresh or sea water as a reflecting surface. The reflecting properties of such surfaces are quite different from those of bare ground and require further consideration.

The reflection coefficients ρ_h and ρ_v for sea water having conductivity $\sigma = 4$ mhos/m at 13 and 27 MHz are shown in Figs. 23 and 24. It is apparent that the curves in these figures resemble the curves of Figs. 5 and 6 for a highly conducting medium, having $a = \frac{\sigma}{\omega\epsilon'} > 10^2$. For the vertically polarized case, the Brewster angle is well below 2 deg. For horizontal polarization, it is seen that the commonly used approximation $\sigma_h = 1 \angle 180°$ is quite good in this case.

The reflection coefficient for fresh water having conductivity $\sigma = 10^{-2}$ mhos/m at 18 MHz is shown by the curves for $\epsilon_r = 80$ in Figs. 7 and 8. The conductivity of fresh water varies over quite a range, but, except for the very highest values of σ at the low end of the HF range, it can be seen that $a = \frac{\sigma}{\omega\epsilon'} \ll 1$ and the exact values of σ and ω are unimportant. Thus for our purposes fresh water is a low-loss dielectric and the curves for $\epsilon_r = 80$ in Figs. 7 and 8 may be used. For vertical polarization the null at the Brewster angle is quite deep and occurs around 6 deg elevation. For horizontal polarization, the approximation $\sigma_h = 1 \angle 180°$ is not met as well as over sea water, but it is good enough for many purposes.

When the reflecting surface consists of ground of finite conductivity and dielectric constant, covered by a ground screen of finite extent, the situation is more complicated. Reflection coefficients can be found for the ground covered by the screen, and for the ground outside the screen,

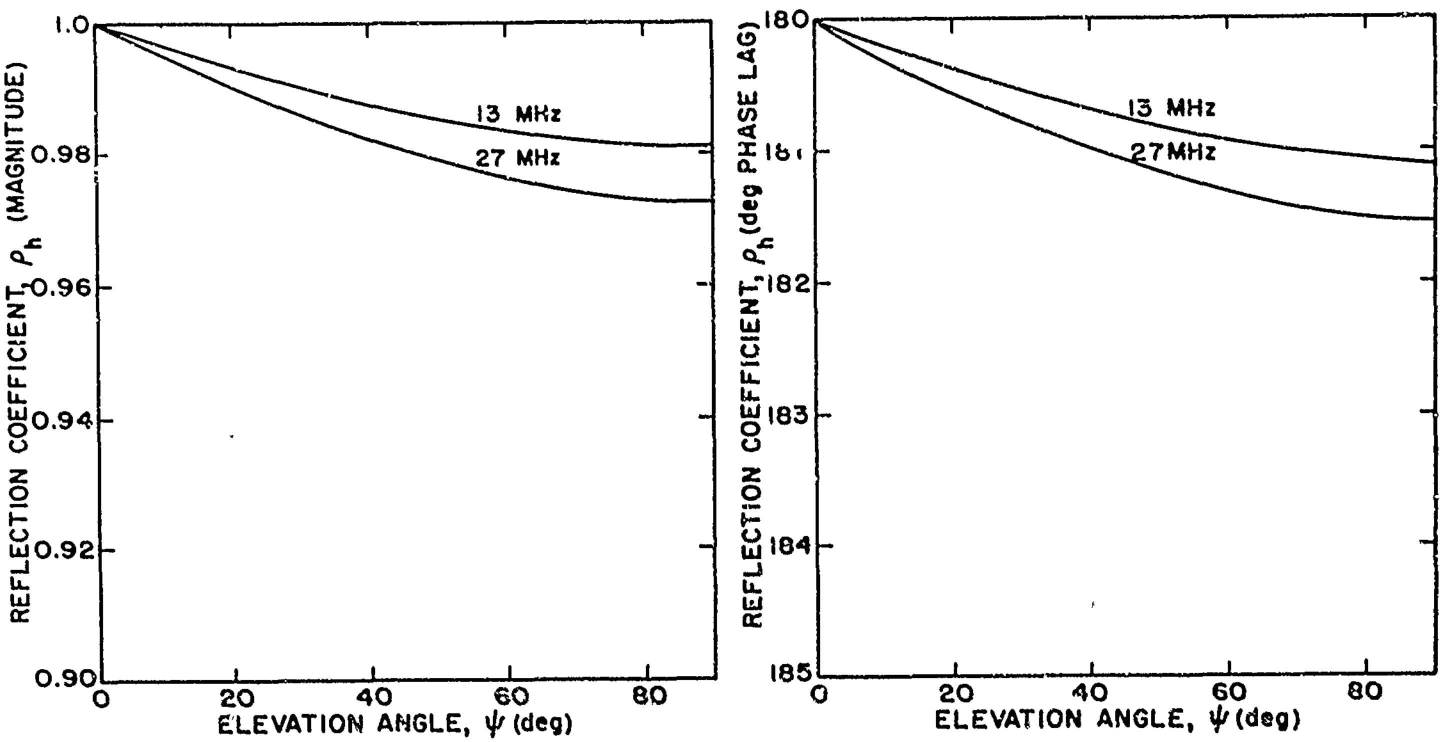


Figure 23. Reflection coefficient ρ_h for horizontal polarization:

OVER SEA WATER.

$\epsilon_r = 80$; $\sigma = 4$ mhos/m.

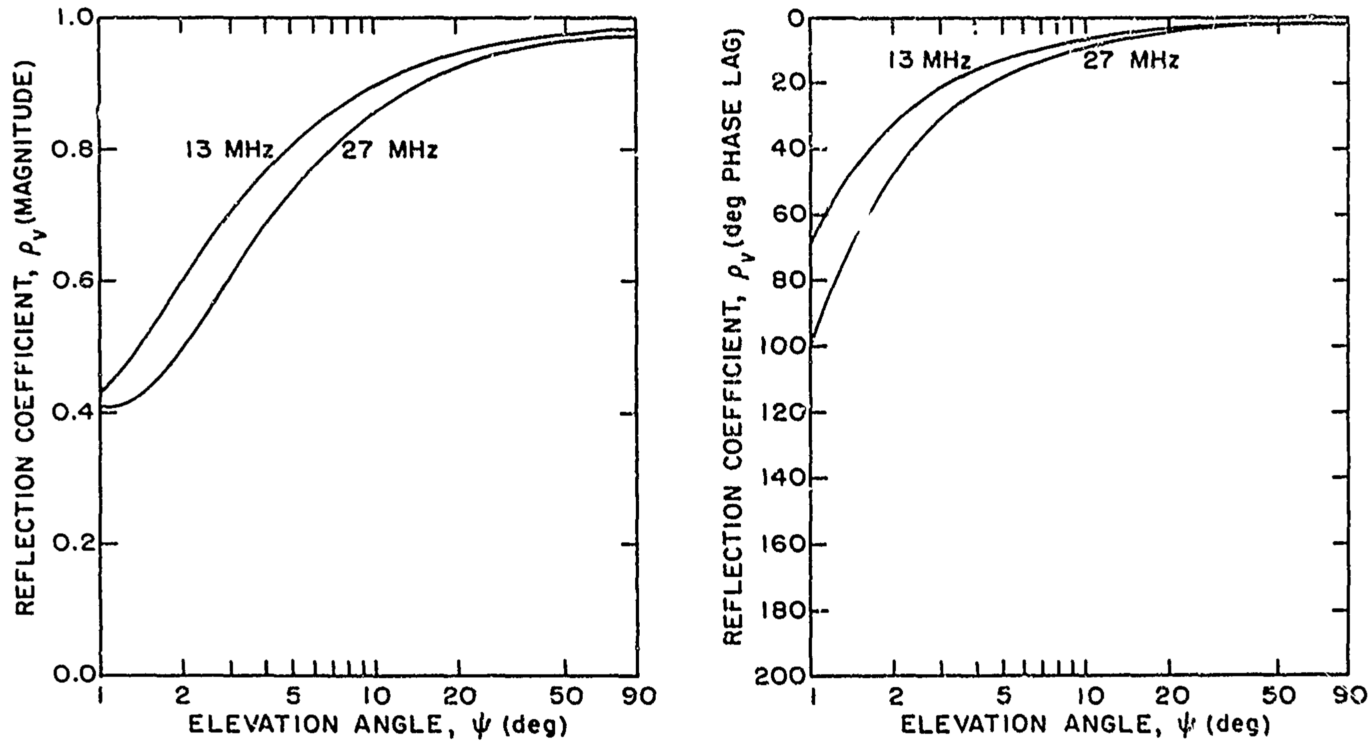


Figure 24. Reflection coefficient ρ_v for vertical polarization:

OVER SEA WATER.

$\epsilon_r = 80$; $\sigma = 4$ mhos/m.

but there will be a discontinuity in the reflection coefficient at the edge of the screen.

It must now be considered that the part of the ground which contributes to reflection in a given direction is not merely a single point, but an area defined by the first Fresnel zone around the point of specular reflection. The radiating element will be at some height h above the ground, and in general it can be seen that for sufficiently high elevation angle ψ the reflecting zone will be entirely on the screen, and for sufficiently low ψ the zone will be entirely on the bare earth; but for intermediate angles the zone will be partly on and partly off the screen. The range of angles over which the transition from screen to no-screen conditions takes place will depend on the antenna height h, and on the shape and extent of the screen.

Calculation of antenna patterns for such cases has been considered by a number of authors, for example Refs. 20-28. Arens [Ref. 21] concludes from other references that effects such as diffraction and reflection occurring at the edge of the screen are small and, from an engineering standpoint, may be neglected. Thus it might be expected that the elevation pattern of an antenna over a finite screen would show a smooth transition from the pattern with infinite screen at high angles to the pattern with no screen at low angles.

Calculation of such antenna patterns is beyond the scope of this report. The reflection coefficient of the infinite screen will be considered, however, since from this a first-order estimate can be made of what a finite screen will do to the patterns of the crossed antenna pair. The derivation of these reflection coefficients is given in Appendix A.

Figure 25 gives the reflection coefficients for vertical polarization for a 1-foot-square mesh of #12 wire, for a 2-foot-square mesh,

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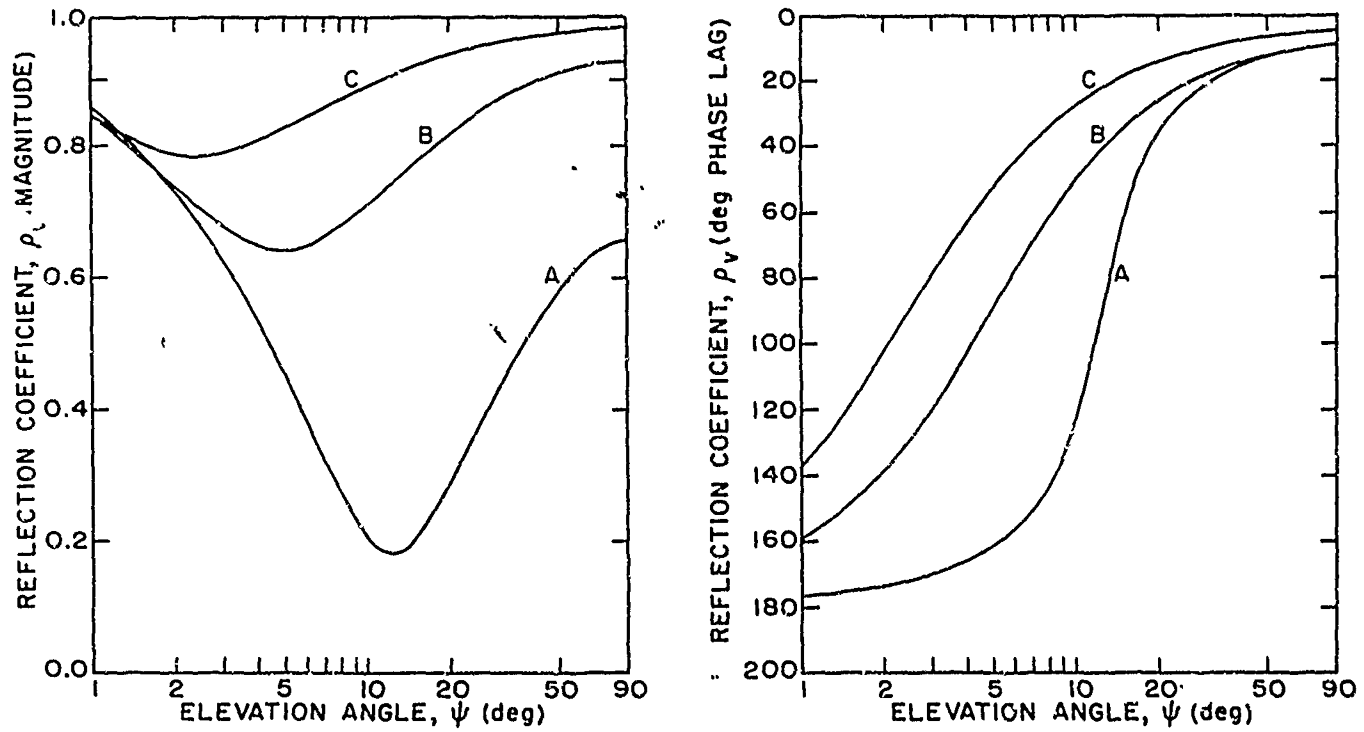


Figure 25. Reflection coefficient ρ_v for vertical polarization:

GROUND SCREEN OVER "GOOD" GROUND.

$f = 13$ MHz; $\epsilon_r = 15$; $\sigma = 10^{-2}$ mhos/m.

[A = No screen. B = #12 wire, 2 ft mesh. C = #12 wire, 1 ft mesh.]

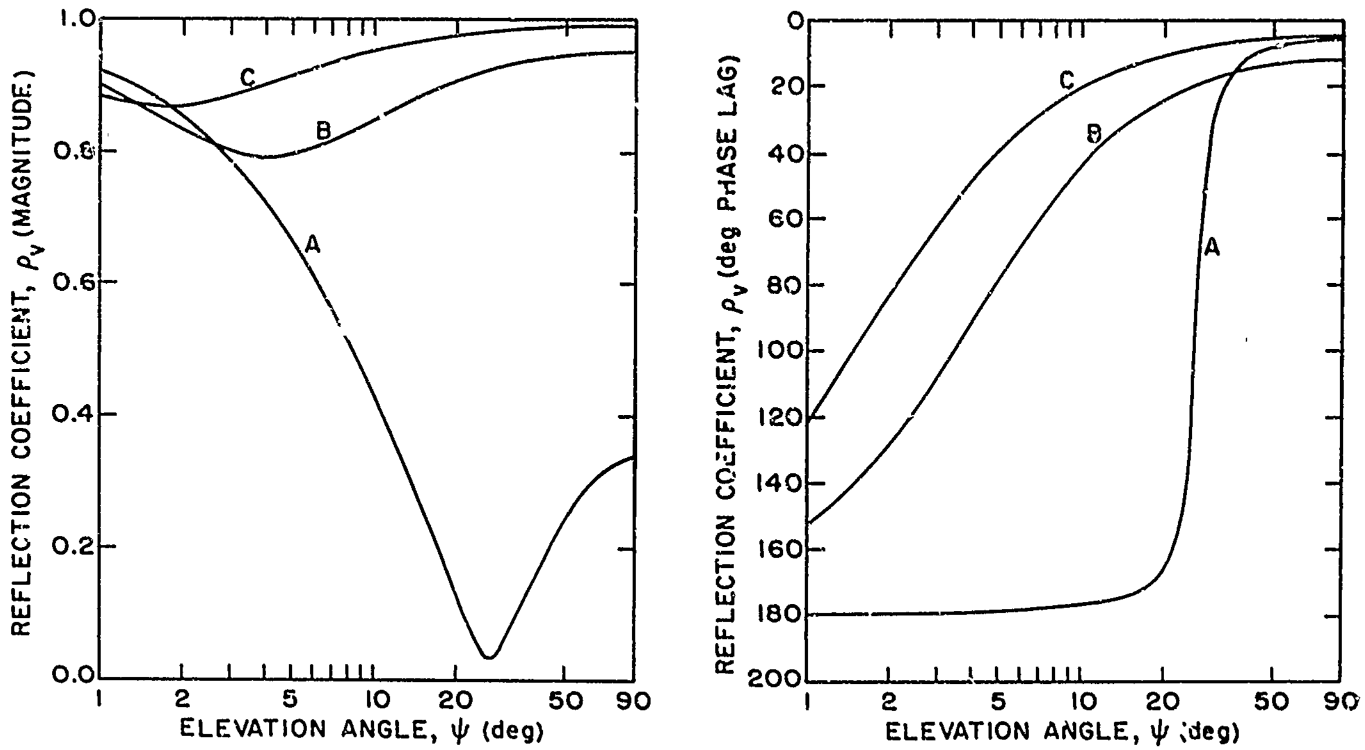


Figure 26. Reflection coefficient ρ_v for vertical polarization:

GROUND SCREEN OVER "POOR" GROUND.

$f = 13$ MHz; $\epsilon_r = 4$; $\sigma = 5 \times 10^{-4}$ mhos/m.

[A = No screen. B = #12 wire, 2 ft mesh. C = #12 wire, 1 ft mesh.]

and for no mesh, over "good" ground having $\epsilon_r = 15$ and $\sigma = 10^{-2}$ mhos/m at a frequency of 13 MHz. Figure 26 shows the same mesh over "poor" ground of $\epsilon_r = 4$ and $\sigma = 5 \times 10^{-4}$ mhos/m, still at 13 MHz. The effect of frequency is shown in Fig. 27 by plotting the 2-foot mesh over "good" ground at 13 and 27 MHz.

Curves were also plotted for horizontal polarization, but are not reproduced here; it was found that the reflection coefficient was close to $1 \angle 180°$ for all the ground-screen cases, and this approximation can be used for engineering purposes.

Figure 28 compares the computed amplitude patterns in elevation for horizontally and vertically polarized antennas of 54 and 76 ft, respectively, over fresh water. The Brewster angle is lower than over ground, about 7 deg, and it is seen that the indentation of the main lobe is more pronounced and occurs at a lower angle than it does over ordinary ground. The amplitude coincidence of the patterns is otherwise not too bad, and it appears that the crossed-antenna pair over fresh water would be useful for a few applications. The phase characteristic of the vertical antenna would be expected to be affected substantially in the vicinity of the notch and minor lobe below about 15 deg, so that operation with circular polarization would not be practical. At higher angles it might be feasible, but the phasing cable length would likely be different than over ordinary ground.

Horizontal and vertical patterns over sea water are shown in Fig. 29. Sea water is a nearly ideal reflector, so that the amplitude nulls and maxima in the pattern become very pronounced. What was merely a small indentation of the nose of the vertical pattern over ordinary ground becomes a deep null over sea water; it is apparent that the amplitude

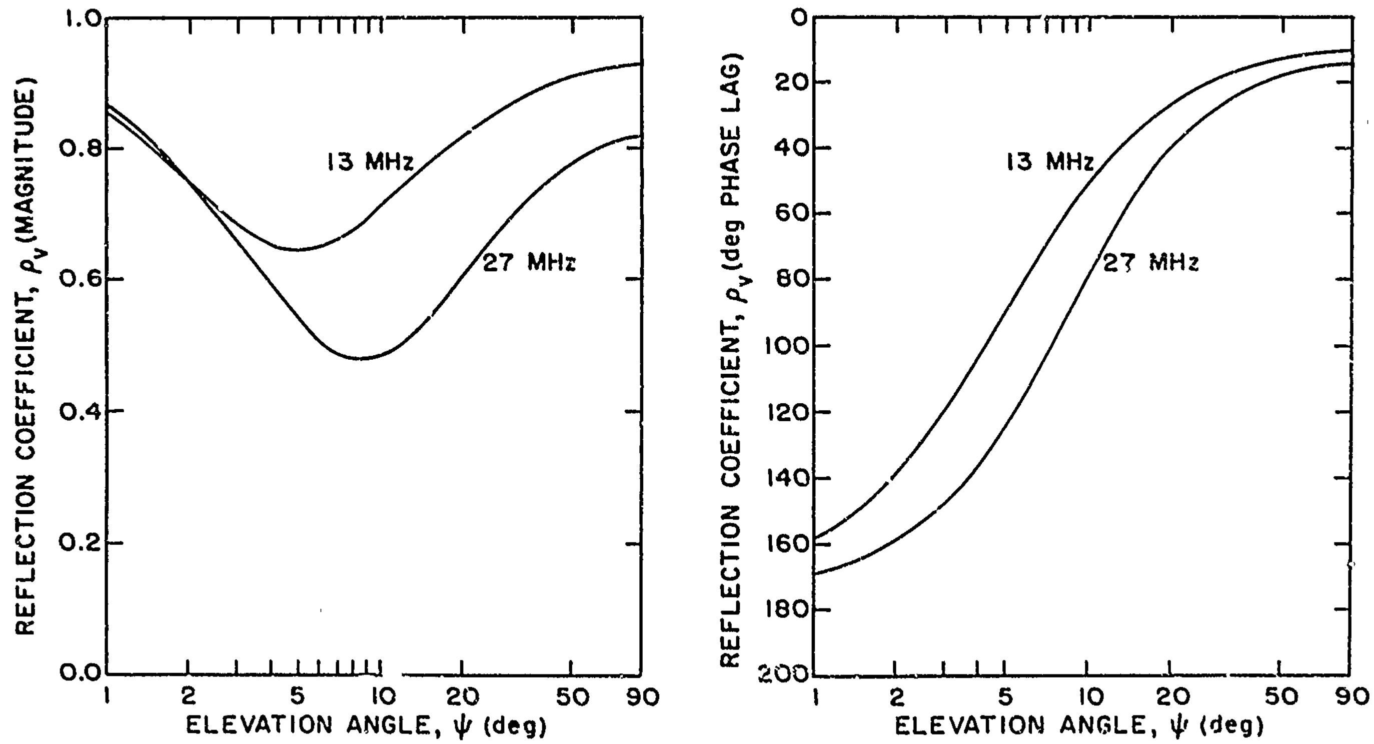


Figure 27. Effect of frequency on reflection coefficient ρ_v for vertical polarization:

GROUND SCREEN OVER "GOOD" GROUND.

$\epsilon_r = 15$; $\sigma = 10^{-2}$ mhos/m.

#12 wire, 2 ft mesh.

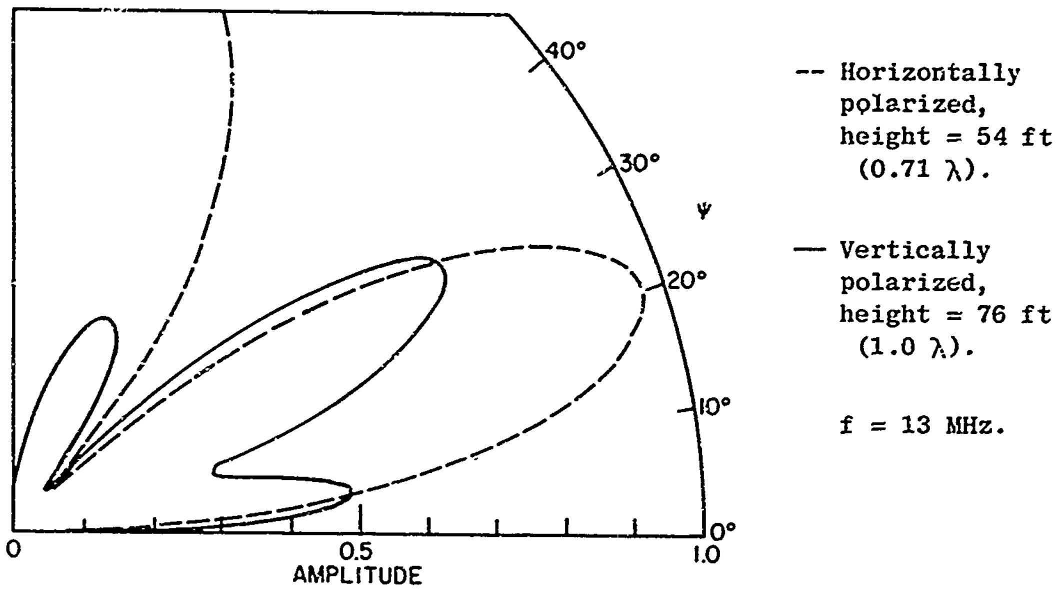


Figure 28. Computed elevation patterns of unequal-height, crossed short dipoles over FRESH WATER.

$\epsilon_r = 80$; $\sigma = 5 \times 10^{-4}$ mhos/m.

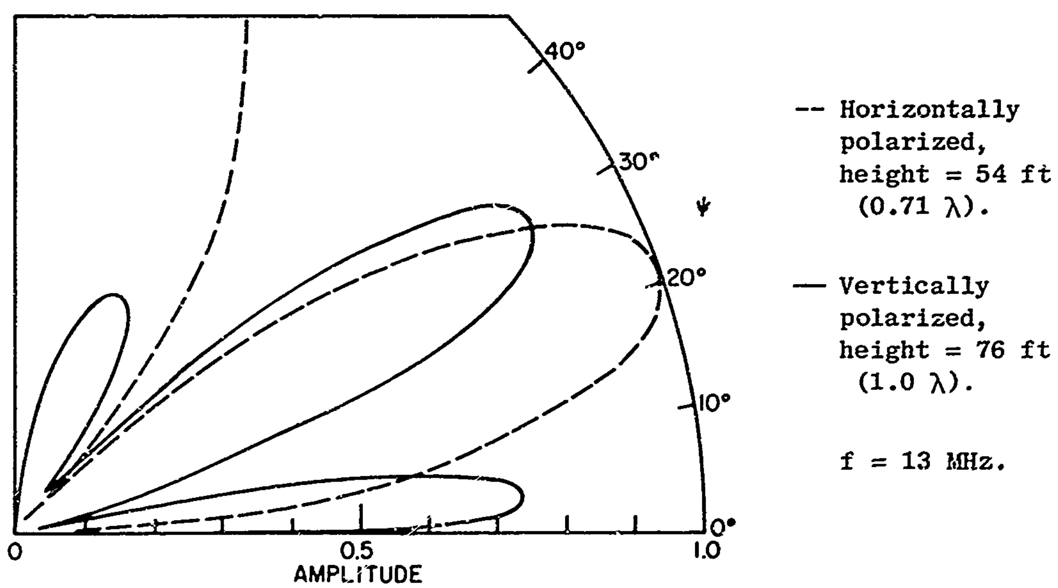


Figure 29. Computed elevation patterns of unequal-height, crossed short dipoles over SEA WATER.

$\epsilon_r = 80$; $\sigma = 4$ mhos/m.

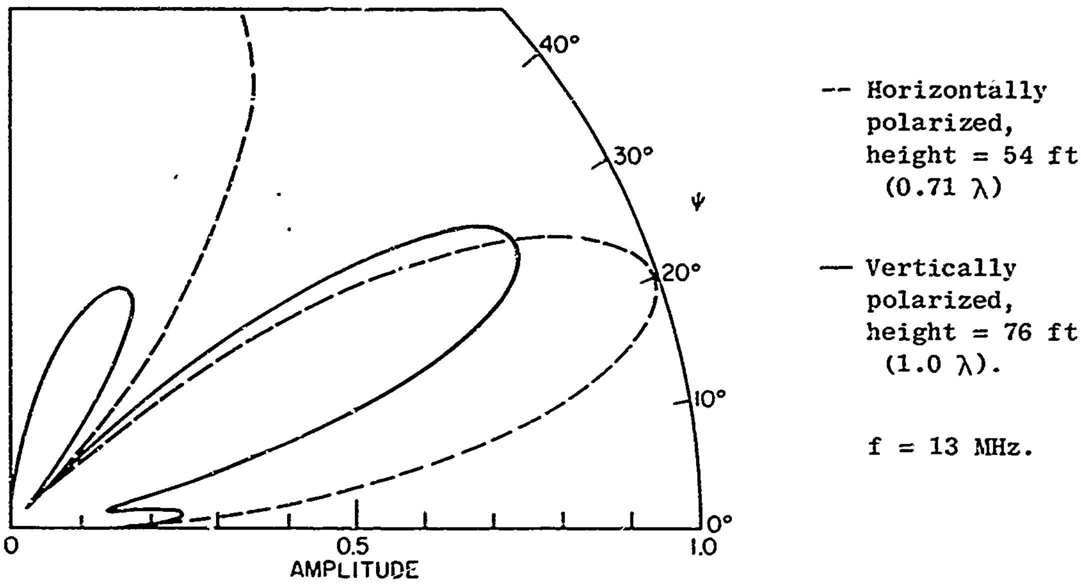


Figure 30. Computed elevation patterns of unequal-height, crossed short dipoles over "GOOD" GROUND COVERED BY GROUND SCREEN.

$\epsilon_r = 15$; $\sigma = 10^{-2}$ mhos/m; #12 wire, 2 ft mesh.

coincidence between the patterns is very poor, and the use of this particular design of crossed antennas is not recommended over sea water.

The horizontal and vertical patterns of the crossed antenna pair over "good" ground covered by a 2-ft mesh screen are given in Fig. 30. This surface, while much closer to an ideal reflector than ordinary ground, is not as good as sea water. The Brewster angle is well below 10 deg. There is a pronounced null at 10 deg and a minor lobe below it; the amplitude matching is passable over only a narrow range of elevation angles, and the phase matching is likely quite poor.

In summary, the crossed antenna pair with heights of 54 ft (horizontally polarized antenna) and 76 ft (vertically polarized antenna), while a fairly good compromise design for use over ordinary ground, is not recommended for operation over fresh water, sea water, or ground covered by a conducting screen.

III. PHYSICAL DESIGN CONSIDERATIONS: ANTENNA CONSTRUCTION AND OPERATION

A. SITE AND STRUCTURE

The antenna should be erected on as flat and level a site as possible. The ground in front of the antenna, over a sector at least 20 degrees on either side of the direction or directions of aim, should be flat out to at least a distance given by

$$d = h \cot \psi \tag{13}$$

where d = distance,

h = height to center of upper antenna

ψ = lowest angle of elevation to be used.

and preferably twice as far. Figure 31 shows the situation. This foreground should be clear of large conducting obstacles such as wire fences, power lines, other antennas, etc., whose largest dimension exceeds one quarter wavelength at the highest operating frequency. The horizon angle seen by the antenna should not be greater than ψ.

As has been discussed in Section II-K, no ground screen is necessary or desirable for proper operation of the antenna.

The antenna structure, an example of which is shown in Fig. 32, should support the upper (vertically polarized) antenna at 76 feet above grade, and the lower (horizontally polarized) antenna at 54 feet, while providing for some adjustment in azimuth. At least that portion of the structure which extends above the lower antenna should be nonconducting, to avoid interfering with the radiation pattern of the vertical antenna.

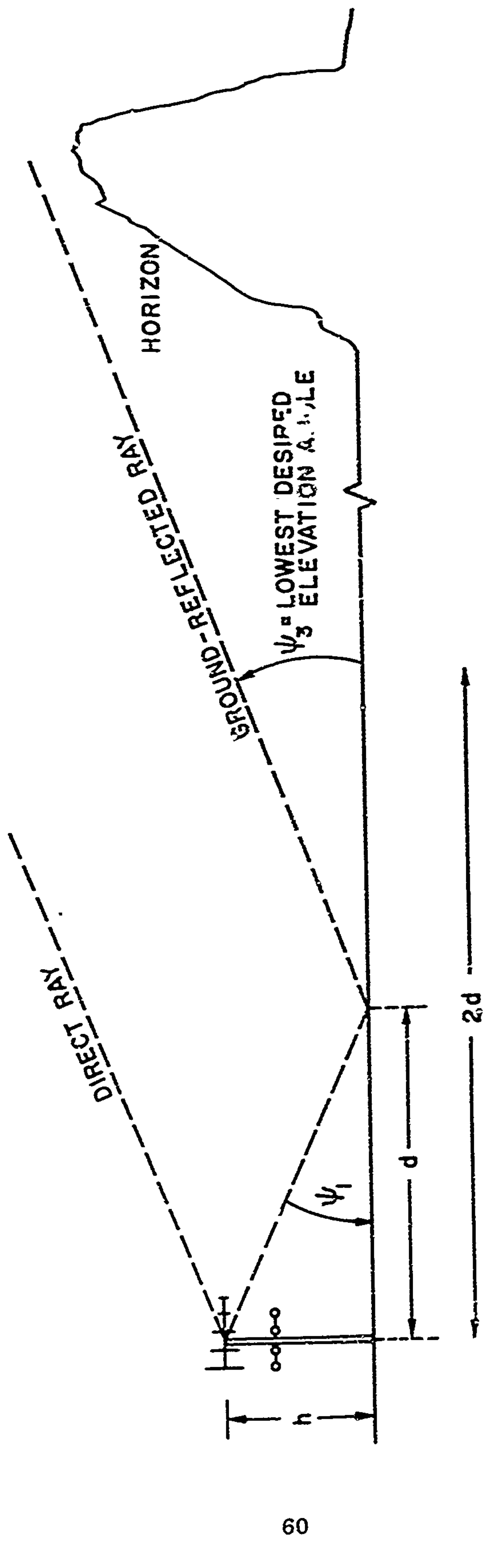


Figure 31. Antenna terrain requirements.

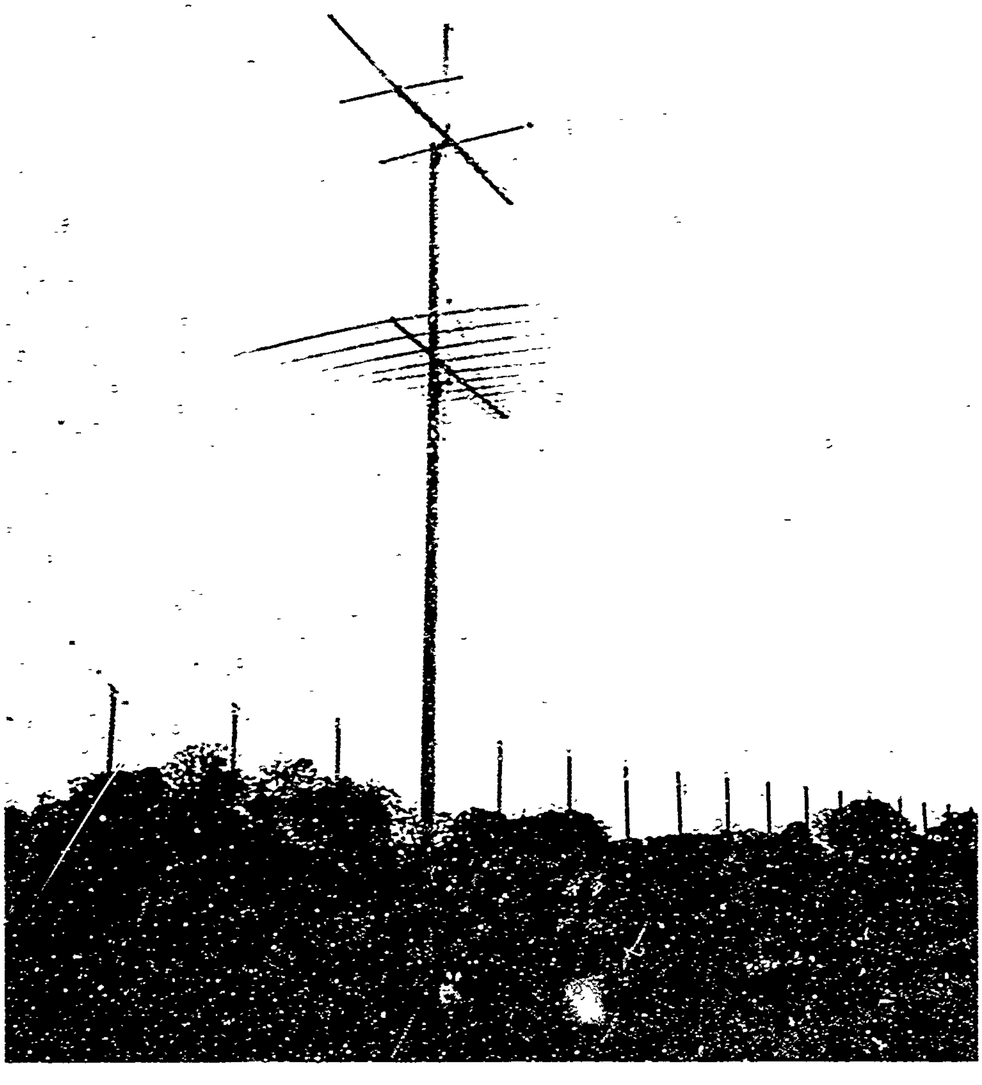


Figure 32. Prototype installation of the unequal-height cross-polarized antenna pair.

Further details of antenna construction and installation are given in Appendix B.

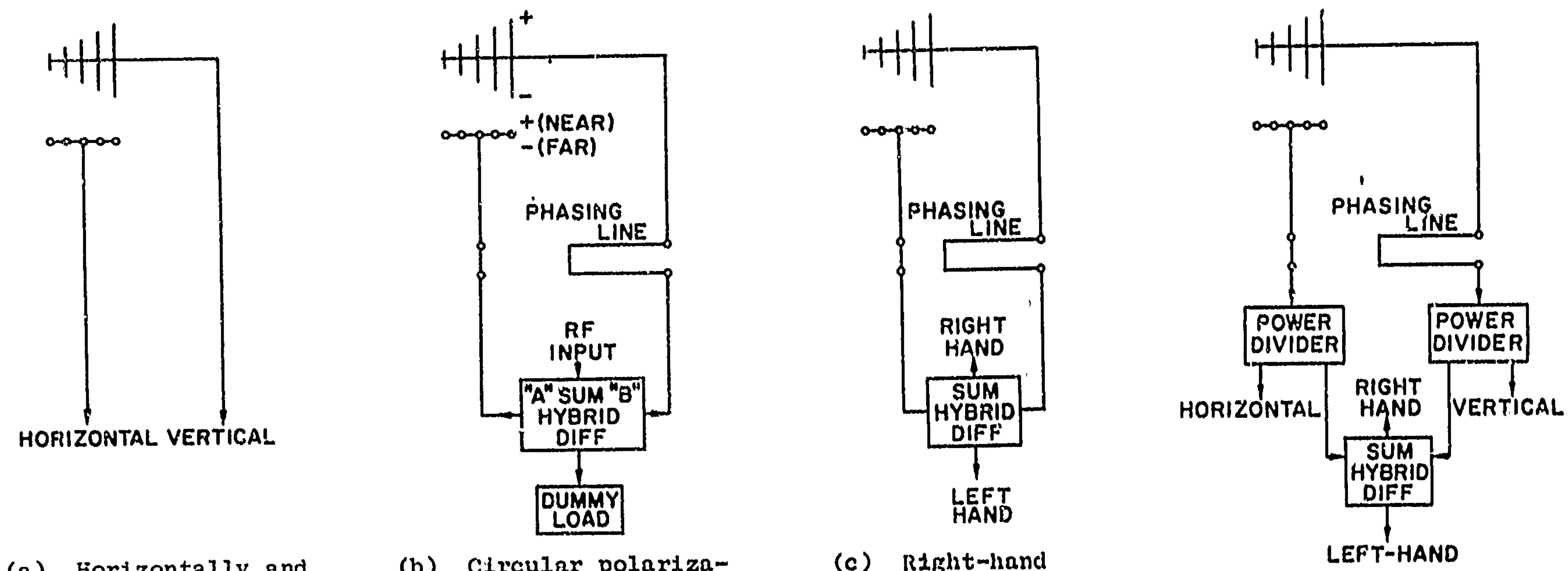
B. SENSE OF ROTATION AND FEEDLINE LENGTH MATCHING FOR CIRCULAR POLARIZATION

When the two antennas are assembled (refer to Appendix B), it will simplify matters if care is taken to feed the cable through the same side of the phasing line for both antennas. Then the outer conductor (braid) of the feed cable must be connected back to the same phasing line that the cable emerges from, and the center conductor of course goes to the other phasing line. When these things are done, if the two antennas were to be erected side by side and fed with identical-length lines, they would radiate in phase. However, the upper antenna must now be twisted 90 deg to orient its elements vertically; let us assume that, looking at the antennas from behind, the upper antenna is rotated 90 deg clockwise.

The proper phase relationship for circularly polarized radiation at a chosen elevation angle and frequency may now be obtained by feeding the two antennas in such phase that the radiated signal from one lags the other by 90 degrees [Ref. 7]. Let this phase relationship be obtained by inserting a length of cable in the feed line to the vertical antenna as already described in Section II-G. (As noted, this connection tends to maintain the phase close to optimum over a wider frequency range.)

By the accepted definition given in Ref. 7, the sense of rotation of a circularly polarized transmitted wave is the direction in which the electric vector is seen to rotate when viewed from behind the antenna, looking in the direction at which the antenna is aimed. With the assumed conditions and for an elevation angle and frequency within the range of the curves of Fig. 19, it will be seen that a transmitted signal going positive at the left end of the horizontal antenna will be followed 1/4 period later by a signal going positive at the top end of the vertical antenna. Therefore the electric vector is seen to rotate clockwise, and right-hand circularly polarized output will be transmitted. By a similar line of reasoning, a right-hand circularly polarized wave will be received from the direction at which the antenna is pointed [Ref. 7].

The usual ways of connecting a transmitter or receiver to the two feed lines are shown in Fig. 33. Horizontally and vertically polarized outputs are available with the connection of Fig. 33(a). Feeding the signal into the sum terminal of a sum-difference hybrid as shown in Fig. 33(b) will give in-phase outputs at the A and B terminals, so that the direction of rotation of the circularly polarized radiated signal can be determined as above. Putting the signal into the difference terminal is equivalent to reversing the phase out of one of the two outputs, therefore it produces the opposite sense of rotation of the radiated signal. For transmitting, a dummy load should always be connected to the unused hybrid terminal as shown. For receiving, both right and left hand circularly polarized outputs are available simultaneously at the sum and difference terminals, as in Fig. 33(c). The mounting and connection of the antennas must be analyzed as above to determine which is which. It is also important to note that after the vertical radiation pattern of either of the antennas passes through a minimum, one could find that the vertically polarized radiation would lead by 90 deg, thus reversing the definition in Fig. 33. The latter will not occur if the operation is constrained within the range of the curves in Fig. 19.



(a) Horizontally and vertically polarized outputs simultaneously for receiving or transmitting.

(b) Circular polarization for transmitting (or receiving). As shown, the signals appear in-phase at "A" and "B" terminals of the hybrid, and right-hand circular output is obtained.

(c) Right-hand and left-hand circular outputs simultaneously for receiving.

(d) Horizontal, vertical, right-hand circular and left-hand circular outputs simultaneously for receiving.

Figure 33. Connection of the cross-polarized antenna for various polarizations.

[Note: The right-handed and left-handed polarizations shown in (b), (c), and (d) will be obtained for antennas oriented and connected as in the example given in the text.]

Two power splitters may be added as in Fig. 33(d) to give simultaneous right circular, left circular, horizontally and vertically polarized outputs to receivers.

Coaxial relays may of course be connected to switch the feed lines between the various polarizations. For transmitting, these should be of the vacuum type and of adequate power capability. It is advisable to arrange the switching so that RF power is automatically shut down while the relays are being switched over. Matching of the lengths of the feedlines should be carried out when the antenna is installed or whenever a line is changed; one inch of line has a phase shift of about one degree at 20 MHz. The matching procedure is described in Appendix B.

C. OPERATION

Practically all the information needed to operate the antenna has been given in the previous sections. It will be summarized here for convenience.

1. The horizontal and vertical arrays should be aimed as exactly as possible in the direction of transmission or reception.
2. The two array feedlines should be connected as in one of the arrangements of Fig. 33 to obtain the desired polarization(s) for transmission or reception.

If circular polarization is to be employed, proceed as follows:

3. The expected height of the reflecting layer at the point of reflection (mid-path in the case of a one-hop path) should be determined by the best available means (refer to Section II-H).

4. The elevation angle ("take-off angle") of the signals should be determined from the distance and the layer height estimate by use of Fig. 21 or by equivalent means.

5. The proper length of cable for the elevation angle and operating frequency should be found from Fig. 19 and connected in series with the feed line to the vertical antenna.

6. The relative amplitudes of the antennas at the given frequency and elevation angle should be made as nearly equal as possible, if necessary by inserting an attenuating pad in the feedline to one of the antennas as discussed in Section II-E preceding.

D. PERFORMANCE

1. Specifications:

(These are taken from the manufacturer's literature on the LP-1007 antenna.)

Frequency range	13 to 30 MHz
Power rating	2 kW average. (This may be modified by the maximum power rating and attenuation of the feed line used.)
Forward gain, nominal, over average soil	13.5 dB
Beam width (half power, average in free space)	
E plane (parallel to the elements)	60°
H plane (perpendicular)	125°

2. Measurements:

VSWR: (Max. rated 2:1) Typically 1.6:1 averaged over the frequency range; see Fig. 34.

FEEDLINE LENGTH MATCHING: Typically ± one inch.

CROSSTALK: 40 dB or more over most of the frequency range; see Fig. 35. NOTE: The measured 40 dB isolation between the crossed antennas is substantially more than that estimated by Bhonsle and Howard for a VHF crossed pair of LPA's on a single boom (25 dB). This is probably due to the physical arrangement, whereby the axes of the two LPA's are separated by 22 ft; the ends of the vertical antenna do not approach the horizontal antenna more closely than about 3 ft, and then are in the neutral plane of the horizontal antenna.

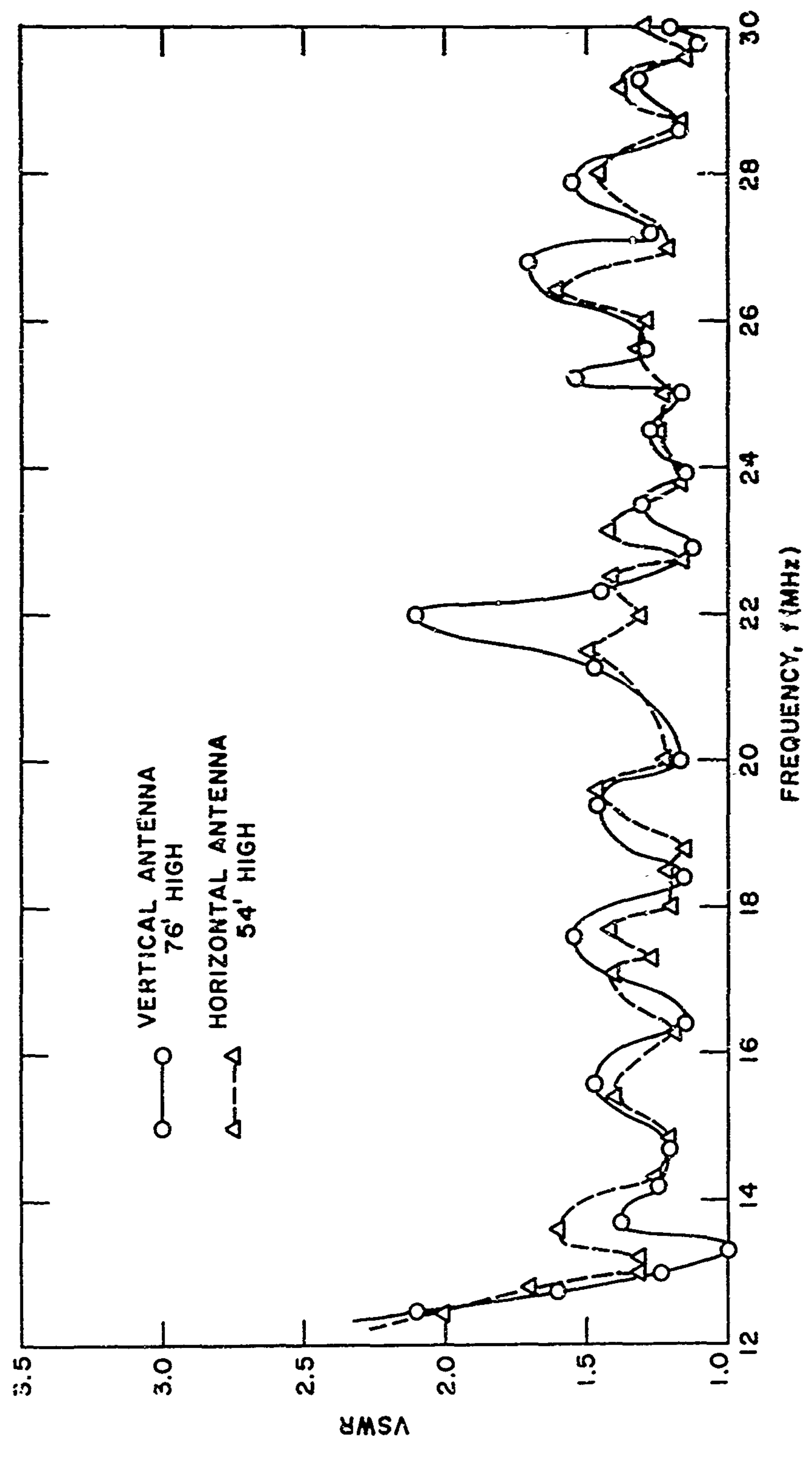


Figure 34. VSWR for cross-polarized LPA's of unequal height.

Lost Hills, Calif.

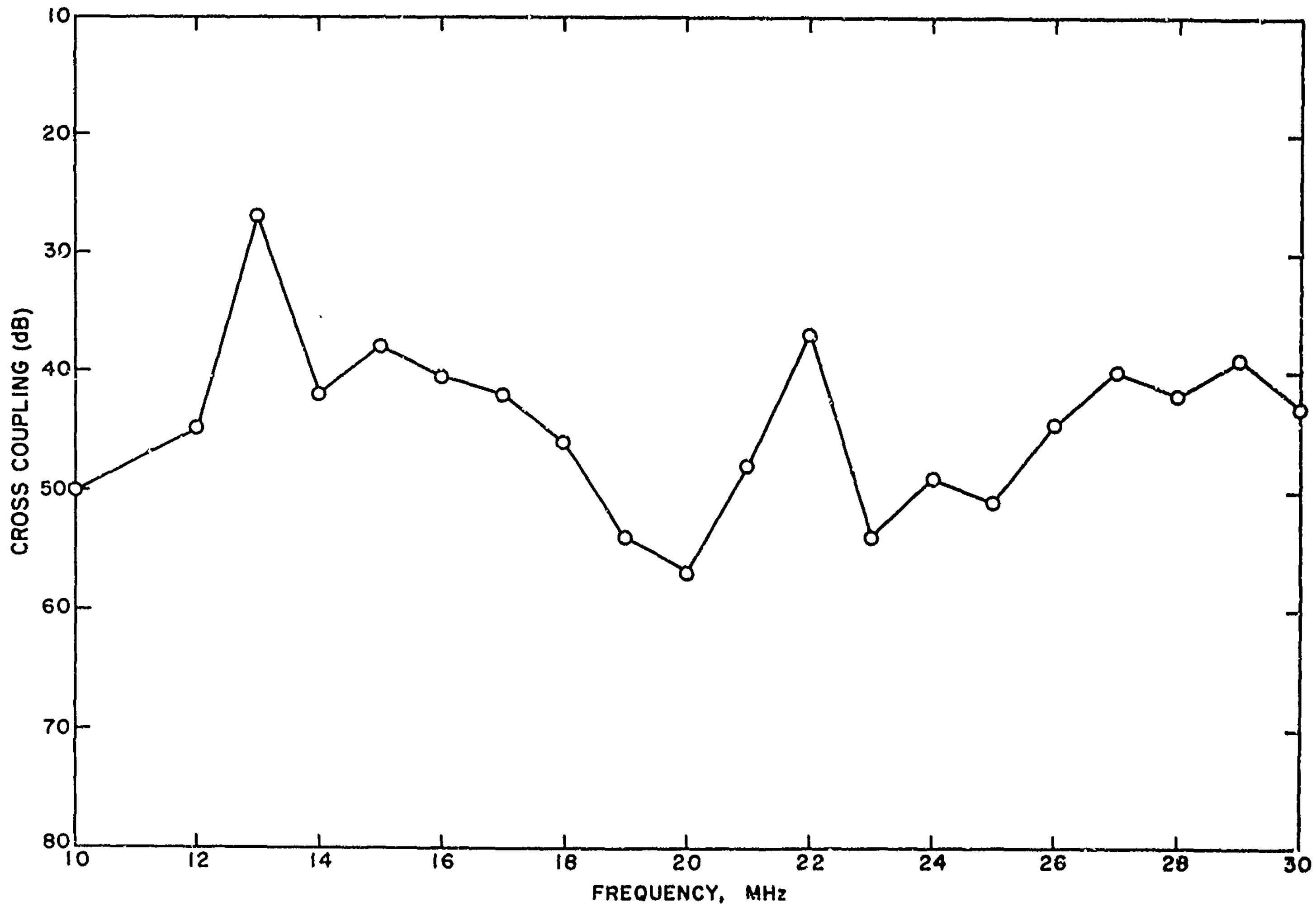


Figure 35. Cross coupling between cross-polarized LPA's of unequal height.

IV. EXPERIMENTAL RESULTS (COMPUTED AND ACTUAL)

There is not a great deal of information available as yet on the actual performance of these antennas. Such measurements and tests as have been made tend to confirm that the performance of the antennas is reasonably in accord with theory.

A. AMPLITUDE RELATIONSHIPS

From the computed elevation patterns of Figs. 9-12 it appears that the horizontal antenna has a greater amplitude response than the vertical, over most of the lowest elevation lobe. The amplitude relationship is plotted directly in Fig. 16 for the same conditions as Figs. 9-12.

It is seen that the amplitude advantage of the horizontal antenna is a function of both elevation angle and frequency; at the lowest elevation angles the vertical antenna has the advantage. When making comparisons, therefore, it is necessary to know as exactly as possible the elevation angle which applies. Also, when making the comparison, it is not easy to be sure what the relative field strengths of the horizontal and vertical components of the arriving signals are; it is not unusual for one of the polarizations to predominate over the other for seconds or minutes at a time. Figures 36 and 37 illustrate the point. These records were taken with a setup like that of Fig. 33(d). A single receiver was switched between the horizontal and vertical antenna outputs, to insure that the gain was the same for both (while another receiver was switched between the two circular polarizations). The receiver was switched 6 sec on horizontal, 4 sec on vertical. Timing marks along the

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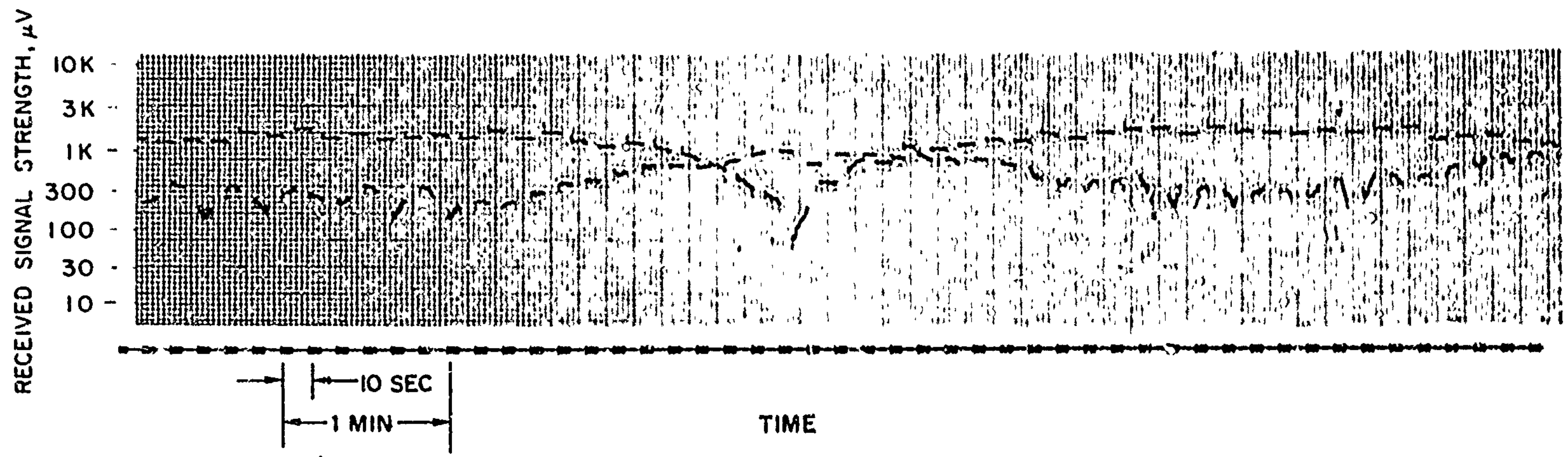
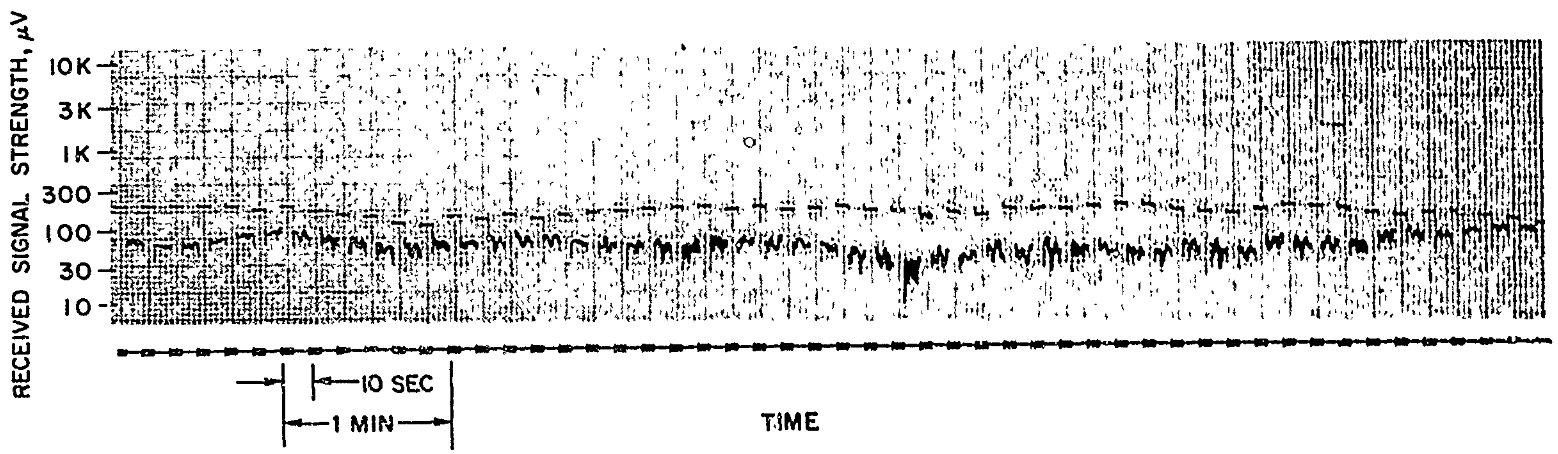


Horizontal signal on for 6 seconds out of 10.
Vertical signal on for 4 seconds, coincident with timing marks at bottom.

Figure 36. Strength of horizontally- and vertically-polarized components of HF signal. 15 MHz signal from WWV, Fort Collins, 1832 to 1840 PST, 20 April 1967. F-layer propagation, elevation angle of arrival approximately 17 degrees.



Horizontal signal on for 6 seconds out of 10.
Vertical signal on for 4 seconds, coincident with timing marks at bottom.

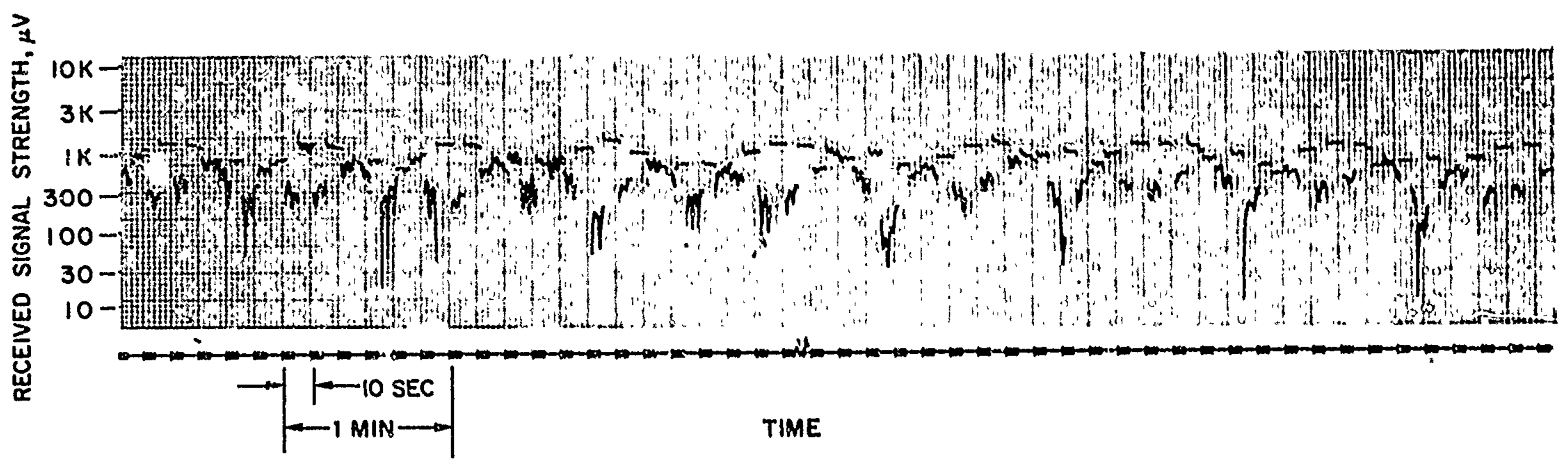
Figure 37. Strength of horizontally and vertically polarized components of HF signal. 15 MHz signal from WWV, Fort Collins, 0833 to 0841 PST, 21 April 1967. E-layer propagation, elevation angle of arrival about 5 degrees.

bottom of the record further identify the vertical interval. The received signal was from WWV, Fort Collins, Colorado, on 15 MHz.

Figure 36 is a record taken at a time when F-layer propagation existed; from ionosonde data the height of the reflecting layer was estimated at 280 km, giving an elevation angle (from Fig. 19) of about 17 deg for the received signal. From Fig. 16 an advantage of about 5 dB for the horizontal signal would be expected, but measurement of the traces of Fig. 36 shows an average advantage of 9 to 10 dB.

On the other hand, Fig. 37 was taken the next morning at a time when E-layer propagation predominated. The height of the reflecting layer was about 115 km, so that the elevation angle was approximately 5.5 deg. Figure 16 shows an expected horizontal-signal advantage of about minus 1 dB in this case; but the horizontal signal measured from Fig. 37 averages about 8 dB less than the vertical signal.

Figure 38, however, shows a situation in which the incoming signal evidently was essentially linearly polarized, with the plane of polarization rotating about once in two minutes; presumably the horizontally and vertically polarized field strengths averaged over several rotations would be substantially equal. Again F-layer propagation existed, with the elevation angle of arrival estimated at 17 deg, and it would be expected from Fig. 16 that the horizontally polarized signal would be about 5 dB stronger. Averaging the levels of the signals in the record of Fig. 38 shows the horizontal signal to be about 2.3 dB stronger. This is fairly typical of experience to date with the antennas; it appears that the horizontally polarized output does average higher over long periods of time, but not always as much as 4 or 5 dB; the range is generally 0 to 4 dB with an average advantage of perhaps 2 dB. Figure 16 thus appears to be a little optimistic in predicting the increased signal level from the horizontal antenna.



Horizontal signal on for 6 seconds out of 10.
Vertical signal on for 4 seconds, coincident with timing marks at bottom.

Figure 38. Strength of horizontally and vertically polarized components of HF signal. 15 MHz signal from WWV, Fort Collins, 1807 to 1815 PST, 20 April 1967. F-layer propagation, elevation angle of arrival approximately 17 degrees.

For circular polarization, it is desirable that the signal levels from the two antennas be as nearly equal as possible. Some improvement under average conditions might be obtained by putting a 2 dB loss pad in the feedline to the horizontal antenna. This has not been done in the observations to date, however, and more experience is needed in this respect. If, under a particular set of conditions, the elevation angle at which circularity was to be optimized were known, it would seem reasonable with present knowledge to select an amplitude equalizing pad to correct for about half the amplitude advantage predicted by Fig. 16.

B. ROTATION OF THE PLANE OF LINEARLY-POLARIZED IONOSPHERICALLY-PROPAGATED SIGNALS

Experiments were performed by Epstein [Ref. 5] during March and April 1967 to confirm the existence of polarization rotation with frequency. High-frequency oblique soundings were made by the FMCW method [Ref. 29] over a path from Lubbock, Texas to Stanford. Amplitude-vs-frequency records of individual modes of propagation were obtained. Figures 39, 40, and 41, reproduced from Refs. 5 and 6, are typical of the results.

To obtain Fig. 39, a single receiver was switched alternately between the horizontal and vertical outputs of the cross-polarized antenna at Stanford. The resulting record demonstrated that when a signal null appears at a given frequency on one of the linearly-polarized antennas, a signal maximum appears at the same frequency on the orthogonal antenna. This suggested that (1) the incoming signal was linearly polarized and (2) the plane of polarization was rotating with frequency. The latter

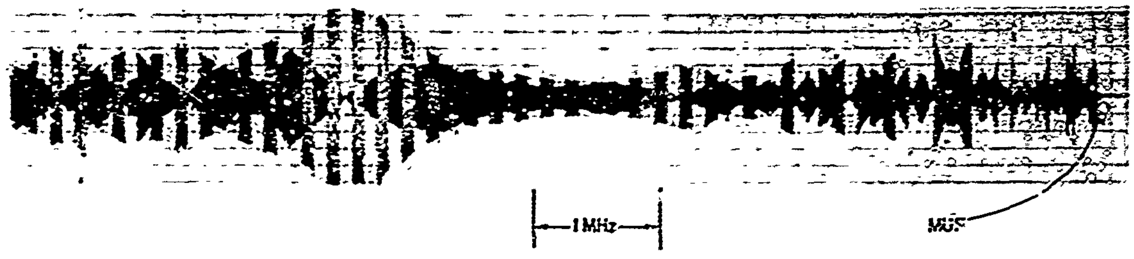


Figure 39. Amplitude versus frequency behavior of the one-hop lower ray during antenna-switching experiment. (From Epstein, TR 143, Stanford University.)

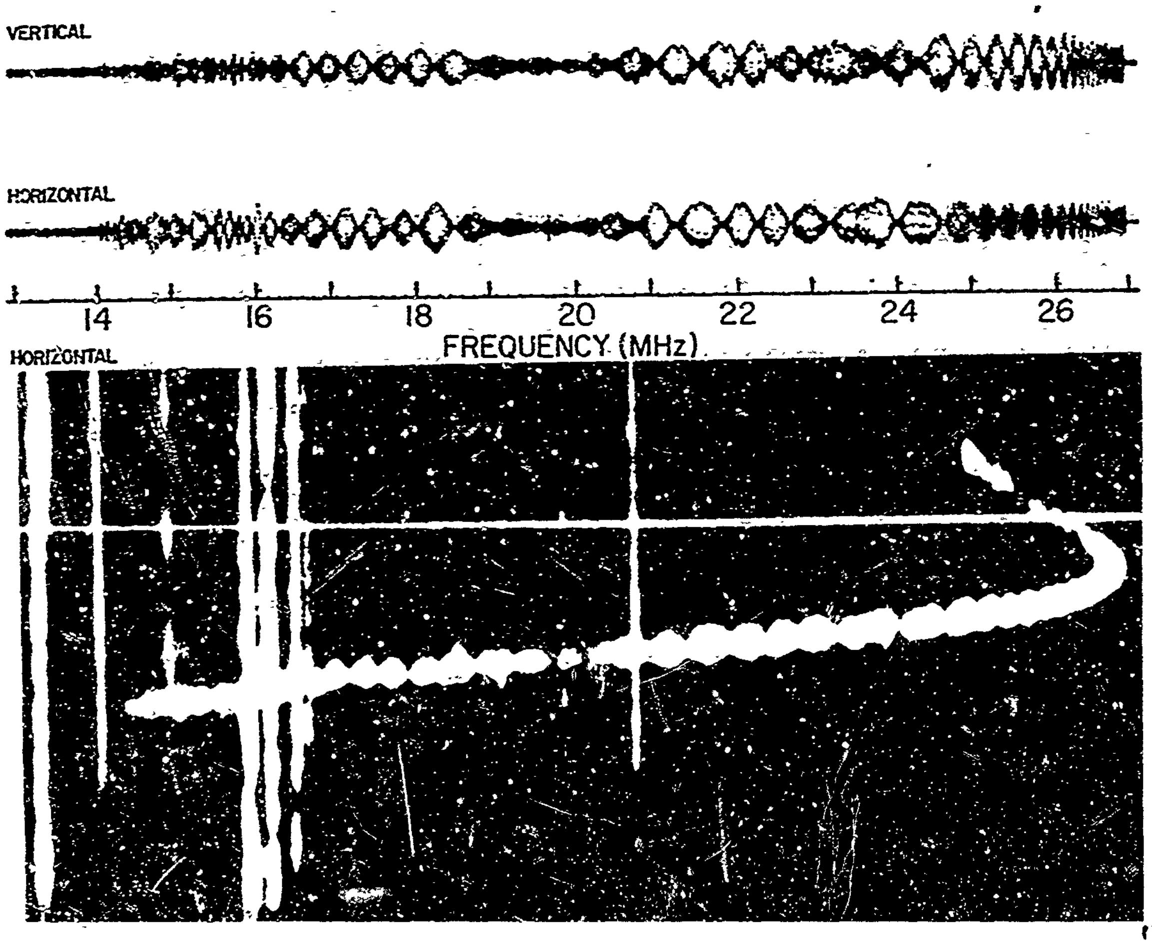


Figure 40. Results of the two-receiver experiment. (From Epstein, TR 143, Stanford University.)

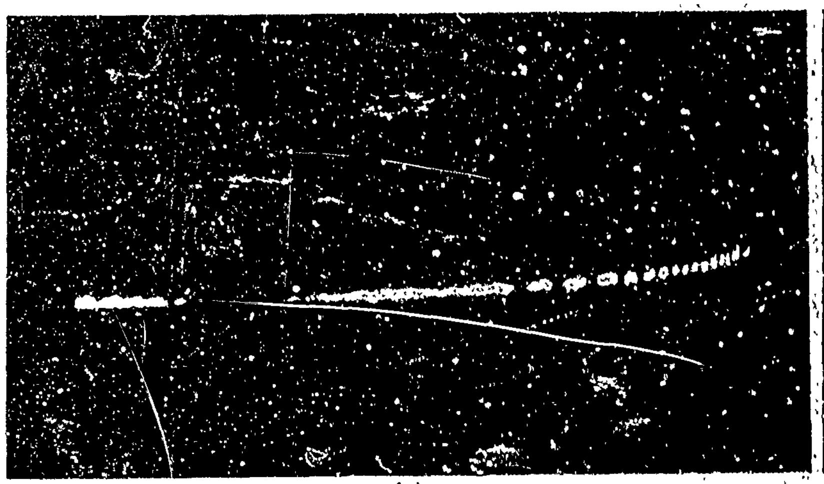
effect was clearly shown, however, only in the slow-rotation region at the left (low frequency) end of the record.

Accordingly, an experiment was performed using two receivers to receive simultaneously on the horizontal and vertical antennas. The amplitude-vs-frequency characteristics of one-hop lower rays received simultaneously in this manner are presented in Fig. 40. Part of the ionogram made from the signals received on the horizontally-polarized antenna is also shown. The amplitude of the horizontally-polarized chart recorded signal can be compared "blob for blob" with the oblique ionogram record. Also, comparison of the horizontal and vertical chart recordings shows more clearly that a null on one record corresponds to a maximum on the other for all frequencies of the one-hop lower ray.

In a third experiment, signals were received simultaneously by four receivers connected to the antenna set up as in Fig. 33(d) for horizontal, vertical, right-band circular and left-hand circular polarizations Figure 41 shows a set of four ionograms resulting from this experiment. The nulls appearing on the records from the linearly-polarized antennas do not appear on those made from the circularly-polarized outputs. This is what would be expected if the assumption of an essentially linearly-polarized incoming wave, with its plane of polarization rotating with frequency, is correct.

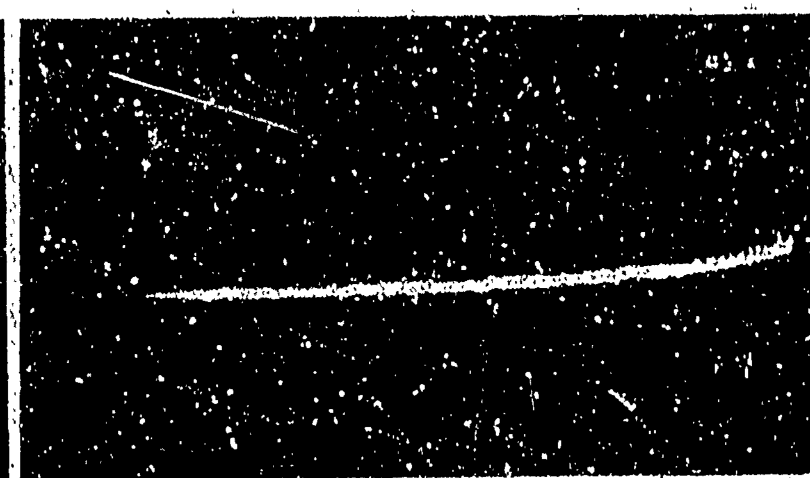
C. SKIP-DISTANCE FOCUSING

If the field strength of an ionospherically-propagated wave is plotted in the vicinity of the "skip distance" (the distance within which, at the particular frequency in use, the ionosphere does not return the signal



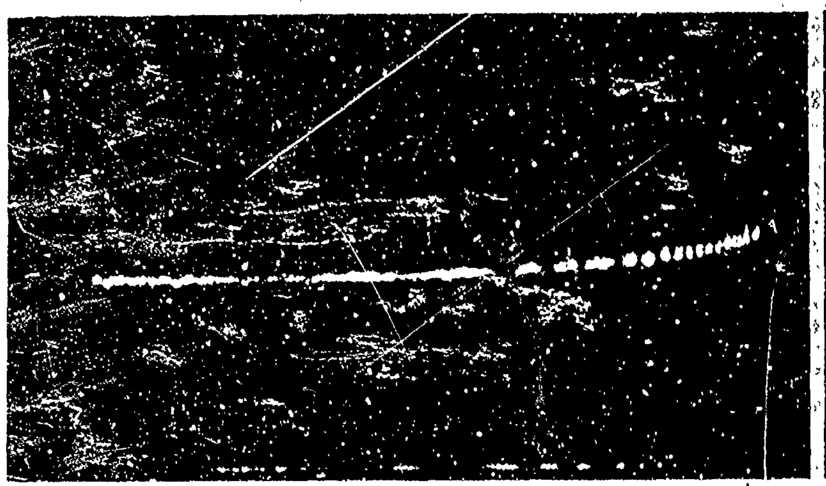
(a)

(a) Vertically polarized



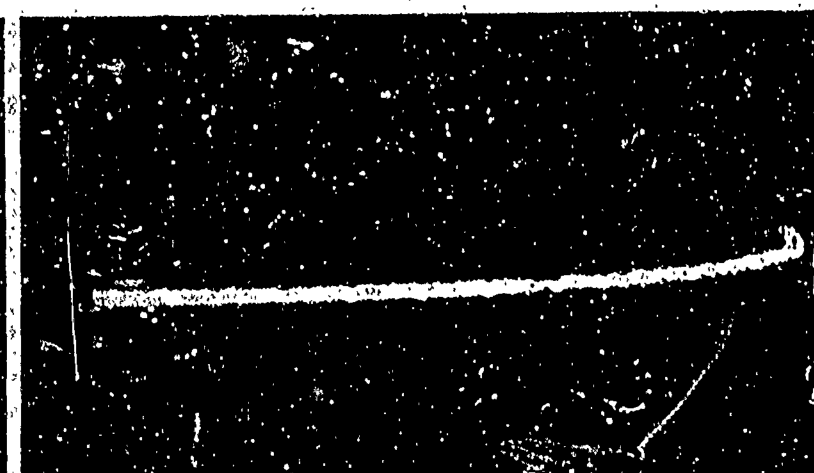
(b)

(b) Left-hand circularly polarized



(c)

(c) Horizontally polarized



(d)

(d) Right-hand circularly polarized

Figure 41. Simultaneous ionograms from linearly and circularly-polarized antennas. (From Epstein, TR 143, Stanford University.)

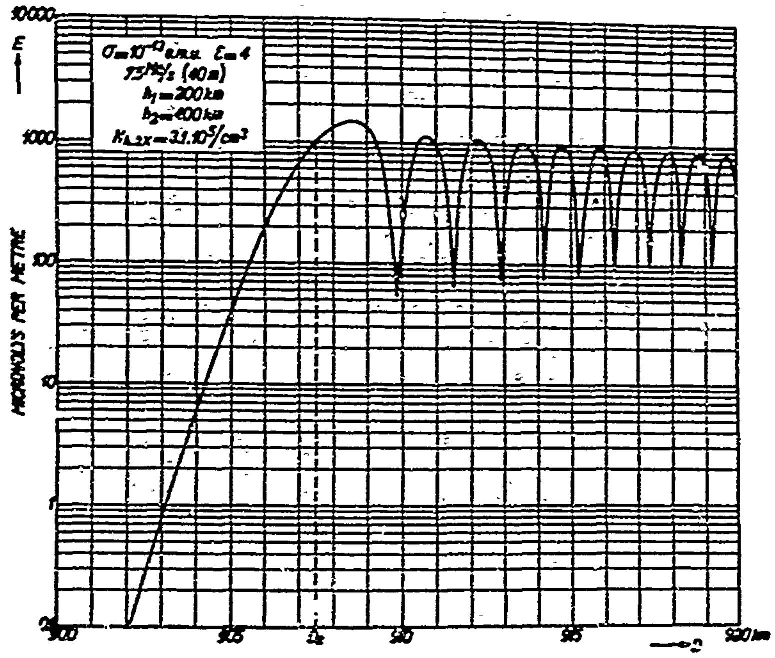
to the earth), the variation of signal strength with distance in the absence of the geomagnetic field would be expected to be as shown in Fig. 42. Within the skip distance the signal level falls off rapidly, while in the illuminated zone the signal strength varies more or less periodically over about a 10 dB range. These variations are caused by interference between the lower and upper (Pedersen) rays. The largest maximum signal strength at the focusing edge just inside the skip distance typically is 6 to 9 dB larger than the average signal level well within the illuminated zone.

If the signal level is recorded during a sunrise or sunset transition, as the focusing edge passes through the receiving location the pattern of signal strength with respect to time would be very similar to Fig. 42. This simple behavior is not often seen in nature for two reasons:

(1) The ionosphere is often in a state of flux which obscures the predicted pattern, and

(2) The presence of the geomagnetic field splits the transmitted wave into two components which follow separate paths, and which individually are more or less circularly polarized with opposite senses of rotation.

Figure 43 shows two superimposed records actually obtained from the right- and left-circularly-polarized outputs of the antenna at Stanford, showing the morning onset of one-hop F2-propagated signal (WWV on 15 MHz) from Fort Collins, Colorado. The skip distance for the extraordinary ray is the shorter of the two. Thus, in the morning, the extraordinary signal is detected first. Since it is more or less completely circularly polarized, it is received best by a circularly polarized antenna of like rotation sense.



The rms field in the neighborhood of the skip distance.

(After H. Bremmer, 1949, Fig. 72, Terrestrial Radio Waves, Elsevier Publ. Co.).

Figure 42. Variation of signal strength with distance in vicinity of "skip distance." (See Ref. 21.)

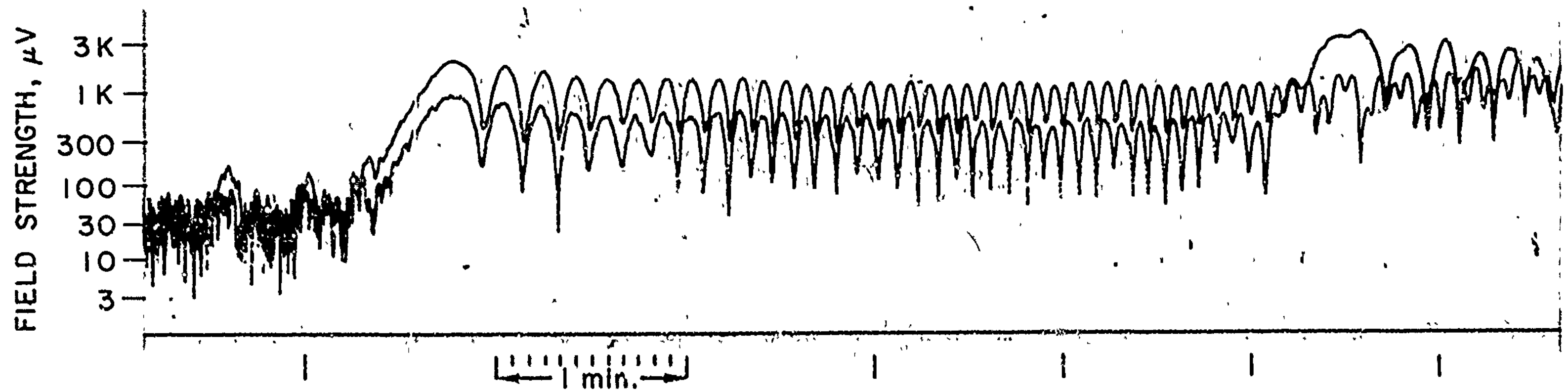


Figure 43. Field strength of right-hand and left-hand circularly polarized components during morning onset of one-hop F2-propagated signal from Boulder, Colorado (received at Stanford on 15 MHz).

The separation of the extraordinary and ordinary components by the antenna was not complete, so that the extraordinary ray does appear somewhat (lower trace in the center portion of Fig. 43) in the output of the antenna which is supposed to be sensitive only to the ordinary ray. It is seen that the other output, supposed to be sensitive to the extraordinary ray, favors this ray by about 10 dB, showing that the antenna patterns were elliptical rather than truly circular.

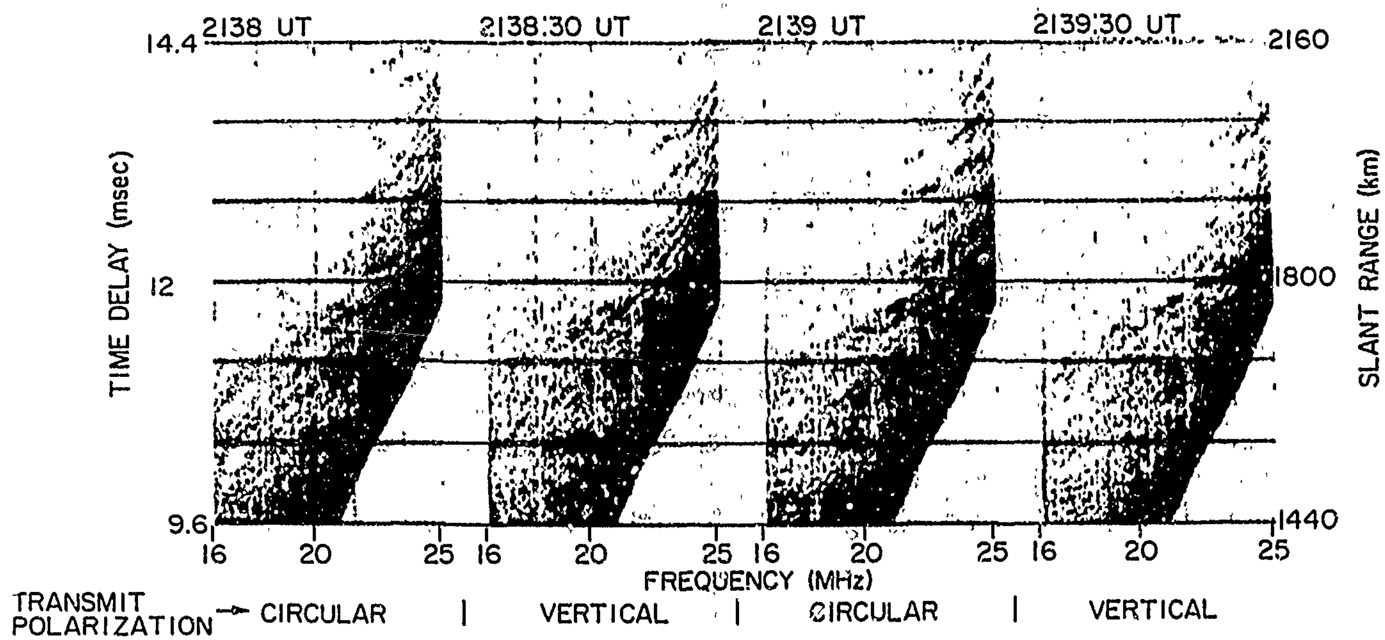
Comparing the experimental record of Fig. 43 with Fig. 42, which is a theoretical calculation based on wave theory, it is seen that the two patterns are remarkably similar when allowances are made for the effect of the geomagnetic field on Fig. 43. Apparently during this transition the ionosphere was unusually calm, so that the predictions of the simple theory could be validated.

D. OCEAN BACKSCATTER

In addition to the experiments performed over one-way oblique paths, the second author of this paper (Barnum) has obtained some interesting results in backscatter experiments which used the crossed-LPA system. [See also Ref. 30.] The transmitter was located at Lost Hills, California and fed 5 kW into one or the other (or both) of the crossed LPA's, which were aimed westward to illuminate the Pacific Ocean. The receiver was located at Los Baños, California, and used a 256-element, 2.6 km aperture array, whose 6 dB beamwidth was of the order of 0.5 deg. It has been found that this beamwidth is narrow enough that modulation of the backscatter amplitude caused by polarization rotation in the ionosphere can be observed. This effect is a function of both range and frequency, and is almost never seen during the summer. An analysis of polarization rotation effects on the amplitude of backscatter from the sea is presented in Ref. 30. A brief explanation of the effect will be given here to explain the application of the crossed LPA system.

An example of the data obtained is shown in Fig. 44. The data are presented in the form of backscatter group time delay vs radio frequency, where the relative amplitude is shown as a density modulation. The dynamic range of this display is about 10 dB. Each record shown differs from its neighbor by 30 sec. On alternate sweeps, the transmitted polarization was switched from vertical to circular as denoted beneath each frame, while the receiving polarization was always vertical. However, the circular polarization actually transmitted was in general not perfectly circular, but elliptical. Theoretical computer calculations showed that "matching" the ionosphere's limiting polarization (beneath the E region) requires nearly circular polarization. However, calculation of the antenna patterns for the phasing line in use showed that the transmitted polarization was approximately circular for only certain regions of the data. Assuming an average ground underneath the antennas, it was calculated that the areas of circularity lie at the bottom of the data between 16 and 20 MHz, and at the very top between 22 and 25 MHz. Thus, the polarization changed from nearly circular at the bottom, to linear (but not necessarily vertical) in the middle, to nearly circular at the top (with the sense of rotation reversed).

The families of lines of signal enhancement which appear most clearly in the data for vertical polarization may be understood (approximately) from the following model: The transmitted wave may be viewed as splitting into two oppositely-rotating circularly polarized waves in the ionosphere.



BEARING: 270 DEG.
SWEEP RATE: 250 kHz/sec(EFFECTIVE)
INTEGRATION TIME: 0.25 sec
RESOLUTION LIMIT: 16 μsec

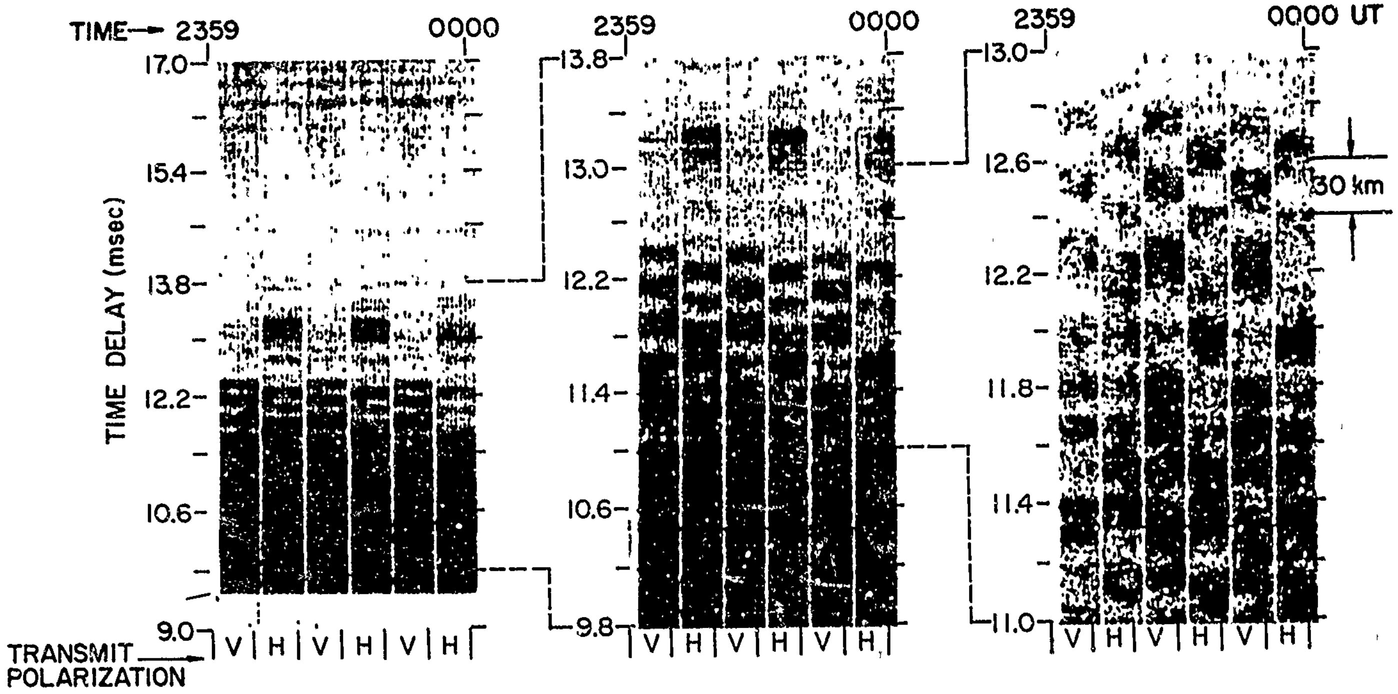
Figure 44. Backscatter from Pacific Ocean, 7 February 1969. [Due to Barnum, Ref. 30.]

These waves travel over different paths to the sea surface. Since the scattering properties of the sea are primarily vertically polarized, the circular waves from the transmitter are linearly polarized after reflection, and these backscatter signals also excite circular waves in the ionosphere. It was shown by Barnum [Ref. 30] that the receiving antenna then combines (in general) four circularly-polarized waves--two left-handed and two right-handed--at each discrete time delay, azimuth, and frequency. Since the time delays of the four modes are equal, the scattering of the individual modes takes place at different ground ranges separated by approximately 500 m. When the four circular modes add at the receiver, the resultant may be considered as two linearly-polarized waves which have undergone a polarization rotation. Since the net rotation changes with both time delay and frequency, there are contours of constant polarization in the range-frequency display. For the monostatic sounder, the contours of maximum amplitude coincide with the contours of constant vertical polarization. (It should also be mentioned that if the sea scatter were not polarization-selective, the contours of signal enhancement should still be visible, but would be double in number. See Ref. 30.)

Although the sounder was assumed above to be monostatic, very similar results should be obtained for the bistatic configuration actually used. It will be found, however, that the polarization characteristics over the transmit and receive paths (along the narrow receive bearing) are different. The net effect is that the spacings of the "polarization lines" will vary with range and frequency in a different manner than for the monostatic case.

The data of Fig. 44 show that when the transmit polarization is switched to nominally circular polarization the character of the lines changes markedly. In fact, nearly 75 per cent of the lines are eliminated, as clearly seen in the frequency region between 22 and 25 MHz, in the upper half of the figure where the transmit polarization was expected to be nearly circular. These results tend to confirm, but do not prove, that the polarization was reasonably circular, since the backscatter results are much more difficult to interpret than the one-way data. However, it can be shown [Ref. 30] that if the polarization rotation is eliminated over one of the bistatic paths, the backscatter amplitude fluctuations should be less steep near the amplitude peaks--approximately as when comparing $\cos^2 \Omega$ to $|\cos \Omega|$, where the polarization rotation angle, Ω, varies with range and frequency. Hence the lines could be broadened out, while maintaining nearly the same spacings, making them more difficult to resolve. It also appears from other work that occasionally the polarization rotation varies over the length of the 2.5 km receiving array, causing the integrated (net) received polarization to be random; this is a rare occurrence, however. One could therefore explain the observed behavior of the lines in Fig. 44 when the polarization is switched, by assuming that the crossed LPA antenna behaved as expected.

Further results are presented in Fig. 45. The arrangement was very similar to that of Fig. 44, except that a very narrow (240 kHz) frequency sweep was used, and the receive bearing was 10 deg north of due west. The data are viewed as if pulses were transmitted which had a 240 kHz bandwidth, with time progressing to the right. Every 10 sec, however, the transmit polarization was switched between vertical and horizontal. The "bars" of signal enhancement with range are a slice taken from line



BEARING AT LOS BAÑOS: 280 DEG.
FREQUENCY: 20.22 MHz
BANDWIDTH: 240 kHz
SWEEP RATE: 250 kHz/sec, 1 SWEEP/sec
INTEGRATION TIME: 0.25, 0.5, 1.0 sec (left to right)
ANTENNA -6 dB BEAMWIDTH: 0.5 DEG.

Figure 45. Controlled-polarization backscatter from the North Pacific Ocean, 4 Nov 1969.

families similar to Fig. 44. The data show that the amplitude fluctuations are due to polarization rotation. Moreover, it is clear that polarization characteristics of the two LPA elements are well defined.

The results of Figs. 44 and 45 show that the crossed LPA system has practical application in backscatter studies, in that the magnitude of the return may be adjusted either to show less marked contours ("circular" polarization), or to obtain enhanced return at ranges where formerly the backscatter was a minimum (switched linear polarization). The results over a one-way path clearly would be analogous, although such a large receiving antenna would not be required to realize the effectiveness of polarization control in the one-way circuit.

V. SUMMARY AND CONCLUSIONS

A requirement existed for a pair of HF antennas having orthogonal polarization, and amplitude and phase characteristics reasonably well matched over the range of elevation angles useful for ionospheric propagation over long paths. Low cost, simplicity of installation and minimum requirements for space and ground screen were considerations.

It was necessary in the evaluation of various antennas to consider the actual reflecting properties of real ground for horizontal and vertical polarization, rather than the idealized properties which suffice for many other purposes.

The design process which led to the selection of the unequal-height cross-polarized antenna pair has been outlined, together with the various theoretical and practical considerations which apply. It has been shown that the antenna pair selected, when operated over ordinary ground, can provide horizontally and vertically polarized patterns which are fairly well matched over the upper part of the HF range. Means of combining the horizontal and vertical antennas while maintaining the proper phase relationship for approximately circular polarization have been described. It has been shown that an acceptable degree of matching for circularity of polarization can be obtained for chosen elevation angles within the main lobe of the elevation pattern, and over a range of frequencies.

It has also been shown that the operation of the antennas is little affected by the parameters (dielectric constant and conductivity) of the ground which forms the reflecting surface, for the normal range of variation of these parameters.

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Operation of the antenna pair over other types of reflecting surface (fresh water, sea water, ground covered by screen) has been considered, and it has been shown that this particular design of antenna pair is not suitable for operation over such surfaces.

Practical aspects of the construction, erection and checkout of the antennas have been covered.

While no detailed pattern measurements of this type of antenna have been made, experiments have been described (including new experiments on ocean backscatter) which tend to confirm that the antenna pair does operate in the manner predicted by the theory.

It is concluded that the crossed-antenna pair which has been described, can, at a reasonable cost and with modest requirements in real estate and in complexity of installation, provide horizontal, vertical, and circularly polarized radiation patterns which are potentially useful for experimental investigations, communication and other applications using long-distance propagation of HF signals.

A P P E N D I C E S

APPENDIX A

THE REFLECTION COEFFICIENTS FOR CONDUCTING SCREEN OVER LOSSY GROUND

A brief summary of the method used to find the reflection coefficients of ground covered by reflecting screen, used in Section II-K, will be shown below. A more detailed exposition will be given in a report by J. R. Barnum now in preparation.

The approach to finding these reflection coefficients is by the concept of surface impedance. Many authors (e.g., Wait and Walters, Ref. 20) define the reflection coefficient for vertical polarization as

$$\rho_v = \frac{\sin \psi_1 - \frac{Z_v}{Z_o}}{\sin \psi_1 + \frac{Z_v}{Z_o}} , \qquad \text{(A1)}$$

where ψ_1 = elevation angle of incident wave

Z_v = impedance of the surface for vertically polarized incident wave,

$Z_o = 120\ \pi$ = impedance of free space.

The surface impedance of the screen is found from equations given by Wait (Ref. 26). The simplifying assumption is made that the spacing d of the screen is much smaller than a wavelength in the ground. The equations are written in slightly different form for convenience in computation.

The surface impedance of the screen over lossy ground is

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$$Z_s = d\,\frac{1 + j}{\delta}\left(\frac{f}{10^7\,\sigma'}\right)^{1/2} + \frac{j4\pi df}{10^7}\,\sin^2\psi_1\left(\ln\frac{d}{2\pi\delta} - RT\right) , \tag{A2}$$

where
$$T = \ln\left(1 - e^{-\frac{2\pi}{d}(2h + \delta)}\right) , \tag{A3}$$

$$R = \frac{\left[1 + \left(\frac{x}{n}\right)^2\right]\left[1 - x^2\right] + \cos^2\psi_1\left[1 - \left(\frac{x}{n}\right)^2\right]^2}{\left[1 + \left(\frac{x}{n}\right)^2\right]\left[1 + x^2\right] - \cos^2\psi_1\left[1 - \left(\frac{x}{n}\right)^2\right]^2} , \tag{A4}$$

and
$$x = \frac{n\sin\psi_1}{\left(n^2 - \cos^2\psi_1\right)^{1/2}} , \tag{A5}$$

where d = spacing between wires, meters,

δ = radius of wire, meters,

σ' = conductivity of wire, mhos/meter,

f = frequency, hertz,

h = height of screen above ground, meters,

n = refractive index of ground = $\sqrt{\epsilon_{rc}}$,

ϵ_{rc} = complex dielectric constant, ϵ/ϵ_o,

ϵ = complex permittivity, farads/meter = $\epsilon'\left(1 - \frac{j\sigma}{\omega\epsilon'}\right)$,

ϵ' = permittivity of the ground,

ϵ_o = permittivity of free space, $8.854\,(10)^{-12}$ farads/meter,

σ = conductivity of the ground, mhos/meter,

ω = $2\pi f$ radians per second.

The surface impedance Z_{gv} of the bare ground for vertical polarization is given by Wait and Walters [Ref. 20] as

$$Z_{gv} = \left(\frac{j\omega\mu_o}{\sigma + j\omega\epsilon'}\right)^{\frac{1}{2}} \left(1 - \frac{j\omega\epsilon_o}{\sigma + j\omega\epsilon'} \cos^2 \psi_1\right)^{\frac{1}{2}} , \quad (A6)$$

where μ_o = permeability of free space.

Wait and Walters point out that, for low radio frequencies and moderate to well-conducting soils, the total surface impedance Z_v for vertically polarized waves may be taken as the parallel combination of Z_s and Z_{gv}, so that

$$Z_v \cong \frac{Z_s Z_{gv}}{Z_s + Z_{gv}} . \quad (A7)$$

This approximation has been used even though the conditions are not exactly met; the error incurred is probably negligible. (This point is discussed further in Ref. 26. Alternatively, since Z_{gv} is large compared to Z_s, $Z_{gv}/(Z_s + Z_{gv})$ may be taken as approximately equal to one, so that $Z_v \cong Z_s$. This is often done.)

The reflection coefficient for horizontal polarization is given by

$$\rho_h = \frac{\sin \psi_1 - \frac{Z_o}{Z_h}}{\sin \psi_1 + \frac{Z_o}{Z_h}} , \quad (A8)$$

where Z_h is the impedance of the surface for a horizontally polarized incident wave. However, for ground screen, $Z_o/Z_h \gg 1$, so that

$$\rho_h \cong - \frac{Z_o/Z_h}{Z_o/Z_h} = -1 = 1 \angle 180^\circ \quad , \tag{A9}$$

which is the commonly used approximation.

It remains to discuss the assumption that the spacing d between wires of the screen is much smaller than a wavelength in the ground. The wavelength λ_g in the ground is related to the free-space wavelength λ_o by

$$\lambda_g = \frac{\lambda_o}{|n|} \quad , \tag{A10}$$

where n is the refractive index of the ground, $\sqrt{\epsilon_{rc}}$. The worst case is for "good" ground; when $\epsilon_r = 15$ and $\sigma = 10^{-2}$, $|n| \cong 4$. At 30 MHz $\lambda_o = 10$ meters and $\lambda_g \cong 2.5$ meters. The largest spacing considered here was $d = 2$ ft $= 0.61$ meter, so that the assumption $d \ll \lambda_g$ was only barely met at 30 MHz.

APPENDIX B

DETAILS OF ANTENNA INSTALLATION

1. ANTENNA SUPPORTING STRUCTURE

Site considerations were discussed in Section III-A. The antenna structure should support the upper (vertically polarized) antenna at 76 ft above grade, and the lower (horizontally polarized) antenna at 54 ft above grade. Class 1 or Class 2 telephone poles have been used in all installations so far. The top of the pole should be not less than 76 ft above grade. An 85 ft pole set 9 ft in the ground is usually satisfactory; if soil conditions make a greater depth advisable, the pole should be correspondingly longer. Good utility practice should be followed in installing the pole. If the soil is unstable, guy wires should be installed, again following utility practice. The guys may be fastened to a clamping ring around the pole at the 50 ft level. Strain insulators should be put in the guy wires 4 ft from the pole and at 8 ft intervals thereafter.

It is advisable to install the antenna brackets and pole steps before erecting the pole.

2. ANTENNA MODIFICATIONS

The particular configuration of the cross-polarized array which has been installed at the various locations consists of two log-periodic arrays, Hy-Gain type LP-1007, one of which is modified for mounting with its elements vertical. The modified, vertically-polarized array is mounted with its boom 76 ft above the ground, while the other array is mounted in the usual horizontal position at 54 ft above the ground. Figure 32 is a photograph of a prototype installation of the antenna. Both antennas are pointed in the same direction, and their mountings are designed so that the antennas can be swung over approximately 60 deg in azimuth. Any greater change in direction requires remounting of the brackets on the pole. Both antennas should be pointed as exactly as possible in the desired direction of transmission or reception.

Modifications to the log-periodic antennas to adapt them for the cross-polarized use are as follows:

1. Special brackets and parts (Figs. 46-49) are made to support the lower (horizontal) antenna to one side of the pole, allowing it to be moved somewhat in azimuth, and to support the upper (vertical) antenna directly above it.

2. The boom-to-mast bracket (manufacturer's part A-1) on the upper antenna is redrilled to fit the pivot bolt on the new special bracket and support the antenna in the vertical position.

3. A 4 × 4 piece of wood is attached to the upper bracket extending up about 8 ft above the antenna mount, and dacron-rope block and tackles are rigged from it to the ends of the antenna boom to provide vertical support. The vertical pipe and diagonal braces, which ordinarily provide vertical support to the antenna when it is mounted in its usual horizontal plane, are not used on the vertical antenna.

4. A rear extension boom about 15 ft long is added at the rear of the upper antenna boom. It should be as light as possible consistent with the necessary mechanical strength. A 12 ft piece of 1/16 in. wall aluminum tubing 1-3/4 in. in diameter, and a 6 ft piece 1-1/2 in. in diameter, both of 2024-T3 alloy, have been used. A dacron rope is run from the top of the 8 ft vertical 4 × 4 to a point 12 ft out on the extension boom to

Figure 46. Special brackets and parts for modifying LPA antennas for cross-polarized use.

A. Vertical antenna mounting bracket.
B. Swivel plate.
C. Boom-to-swivel bracket with 4" × 4" support pocket.

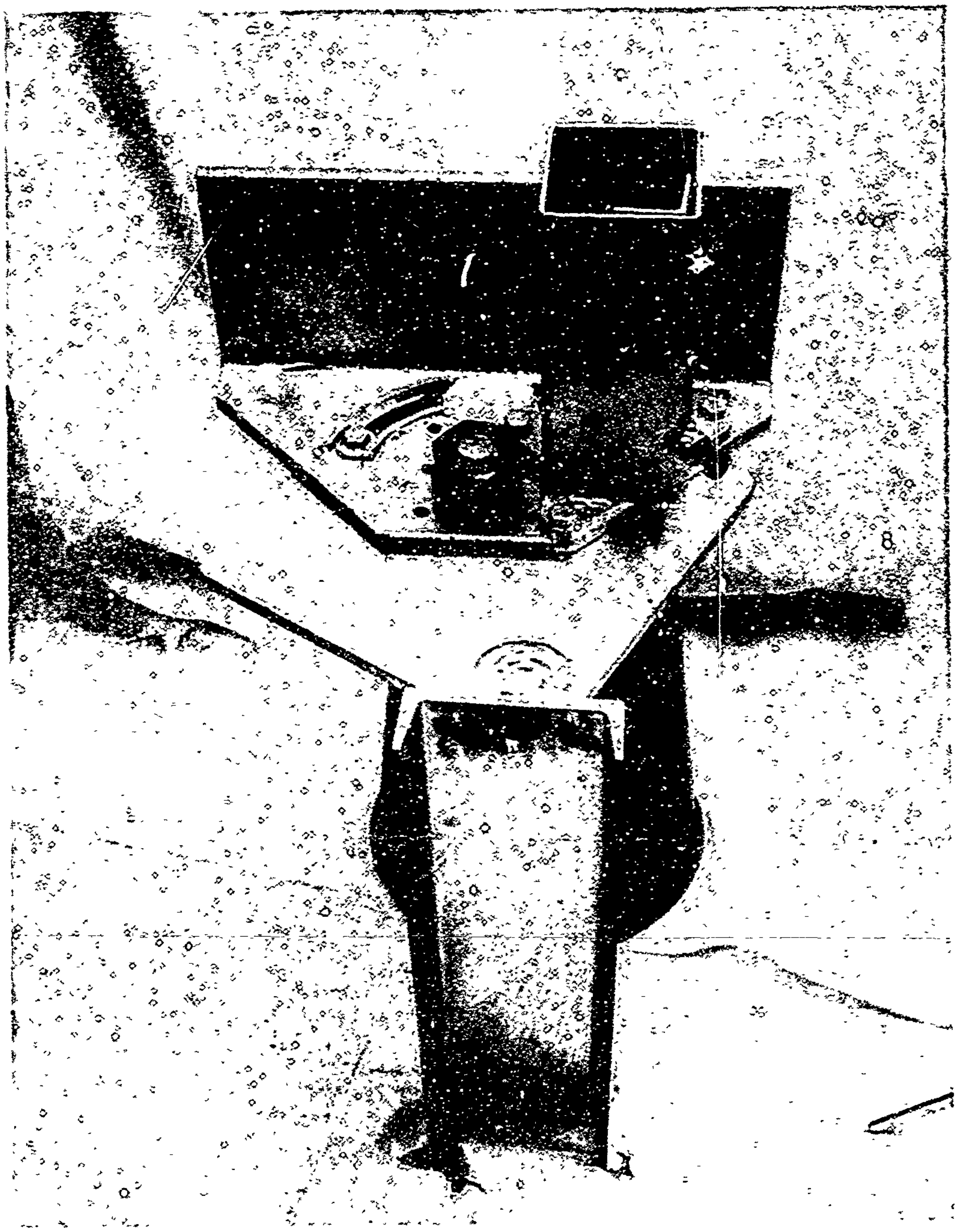


Figure 47. Vertical antenna mount, assembled.

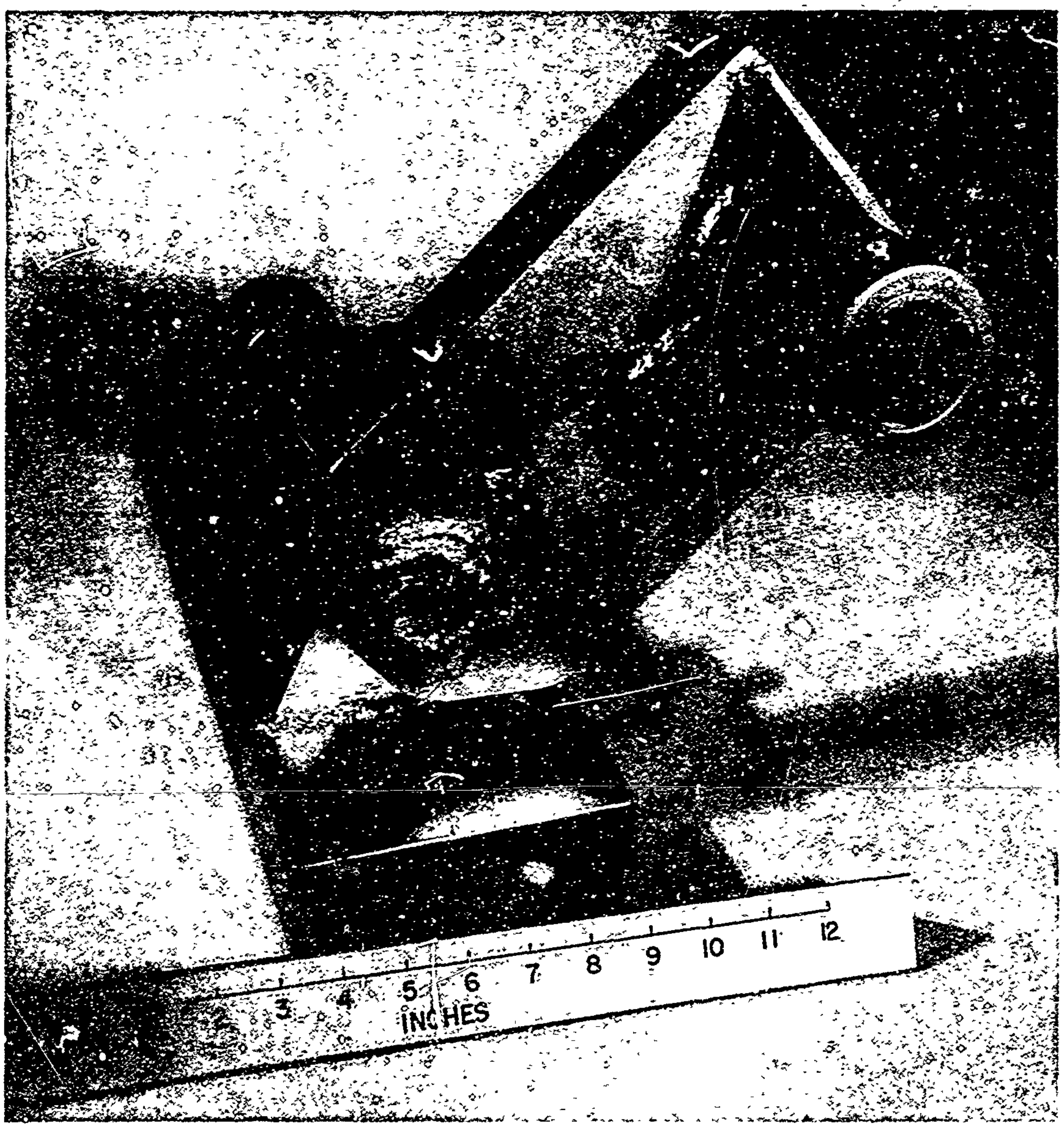


Figure 48. Horizontal antenna mount, assembled.

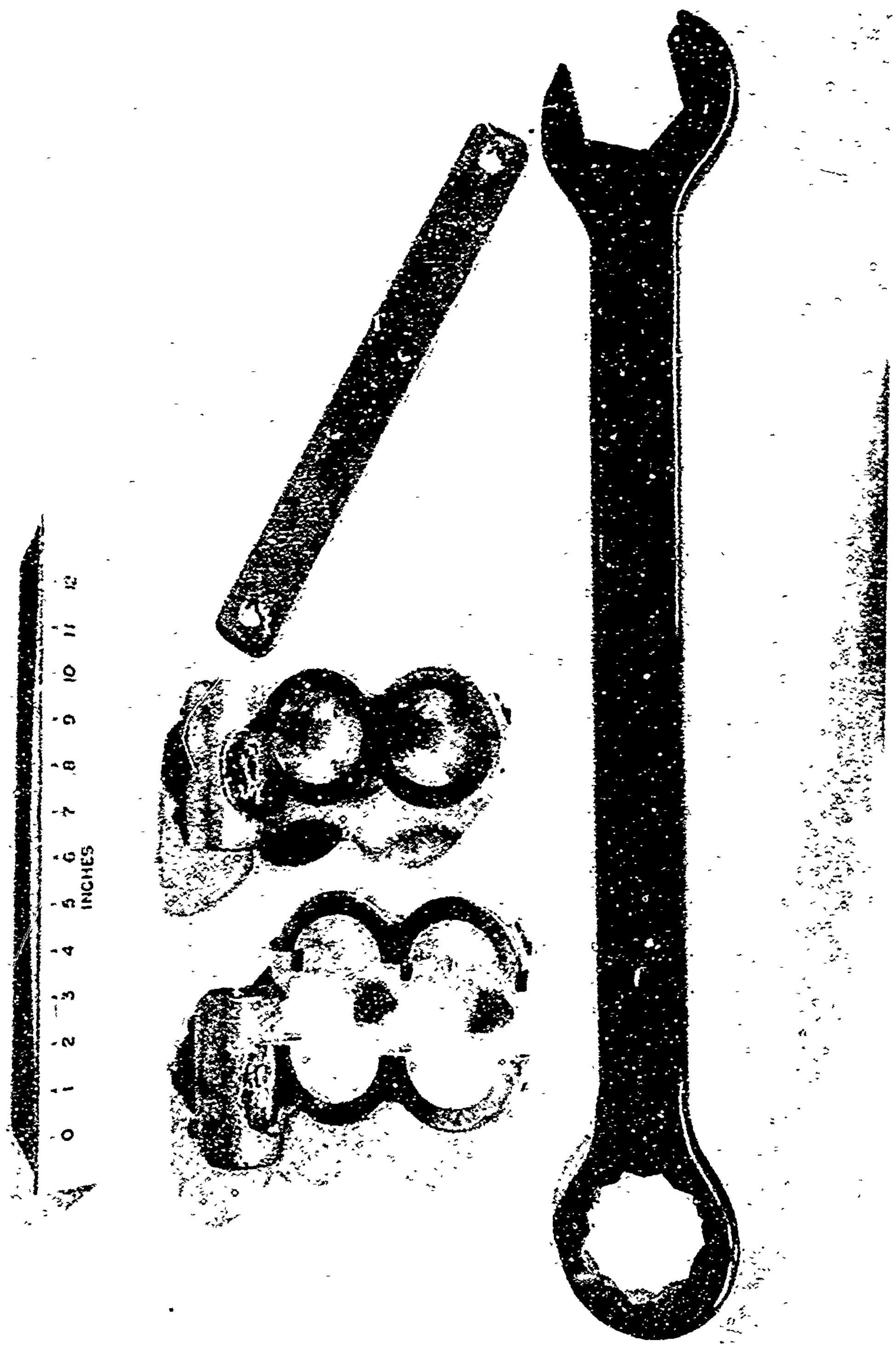


Figure 49. Wrench, boom-to-spar mount, and top pulley bracket for vertical antenna mounting.

support it vertically. The upper antenna feed line is installed in the usual manner, but instead of dropping down from the antenna mount, it is run out along the extension boom, and dropped to the ground from that point. This is to keep the feed line from affecting the directive pattern of the vertical antennas. A suitable strain relief should be provided at the end of the boom to keep the cable from bending sharply at that point, and to keep the weight of the hanging cable off the bend. (The feeder of the horizontal antenna is brought down the pole in the usual manner. The two feeders are made equal in length and the excess cable in the horizontal feed line is coiled up at the base of the pole.)

5. A horizontal spar extending five feet on each side of the boom is installed at the mounting of the vertical antenna, and dacron guys run to the fore and aft ends of the main boom to stiffen it against wind loading. The load on this spar can be quite large; at least one-inch steel pipe is suggested. A similar spar, which may be of lighter material, is put at the rear of the boom and rigged to stiffen the rear extension boom. The ropes are attached at a point 12 ft out on the 15 ft rear boom.

6. The weight and sail area of the auxiliary rear boom put a considerable twisting torque on the mounting of the upper antenna, due to gravity and wind loading. To hold the upper antenna level against the weight of the extension boom and feed line at the rear, a dacron rope is run from the forward end of the boom down to the mounting of the lower antenna. Dacron guys may be installed from the rear extension boom to ground anchor points well out on either side of the antenna, to keep it from swinging in the wind. These guys should be left a trifle slack to allow for swaying of the pole. A possible alternative would be to mount a counterweight on the front of the boom. The counterweight would be of sheet steel, of such an area as to provide a turning moment under wind loading equal to that of the auxiliary boom and feed cable, while its thickness would be enough to counterbalance the gravity load.

7. The cable installed in the two arrays should be a 0.405 in. O.D., 50 ohm cable with a stranded center conductor, such as RG8-A/U. This is almost the largest cable that will pass through the array phasing lines. A continuous 165 ft length of cable is needed to pass through the antenna phasing lines, back out along the extension boom of the vertical array and down to the ground. An equal length of cable should be used for the horizontal array.

   Figure 50 gives the power rating and attenuation of some commonly-used cables. If higher power is to be used than RG-8A/U will accommodate, teflon cable such as RG-87/U may be used instead. At the ground end of the 165 ft cables feeding the arrays, larger-size cable such as RG-17/U may be connected if power-handling or attenuation considerations make it desirable.

8. A messenger cable of thin stranded steel guy wire should be run from the rear of the upper array extension boom to a ground rod directly below, and the vertical feeder lashed to it at short intervals to keep it from whipping in the wind. (This cable also provides lightning protection.) Likewise, the feedline from the horizontal array should be fastened to the pole to prevent wind damage. In one installation it was found necessary to cover this downlead with vinyl tubing (garden hose).

3. ASSEMBLY HINTS

The following hints will be found useful in addition to the assembly instructions normally furnished with the log-periodic antennas:

1. It is essential that all electrical connections at both ends of each jumper wire, at each joint of each element, and at the joints and jumpers of the phasing lines, be perfectly tight and that the metal surfaces at the connections be perfectly clean before assembly. If this is not done, the connections will

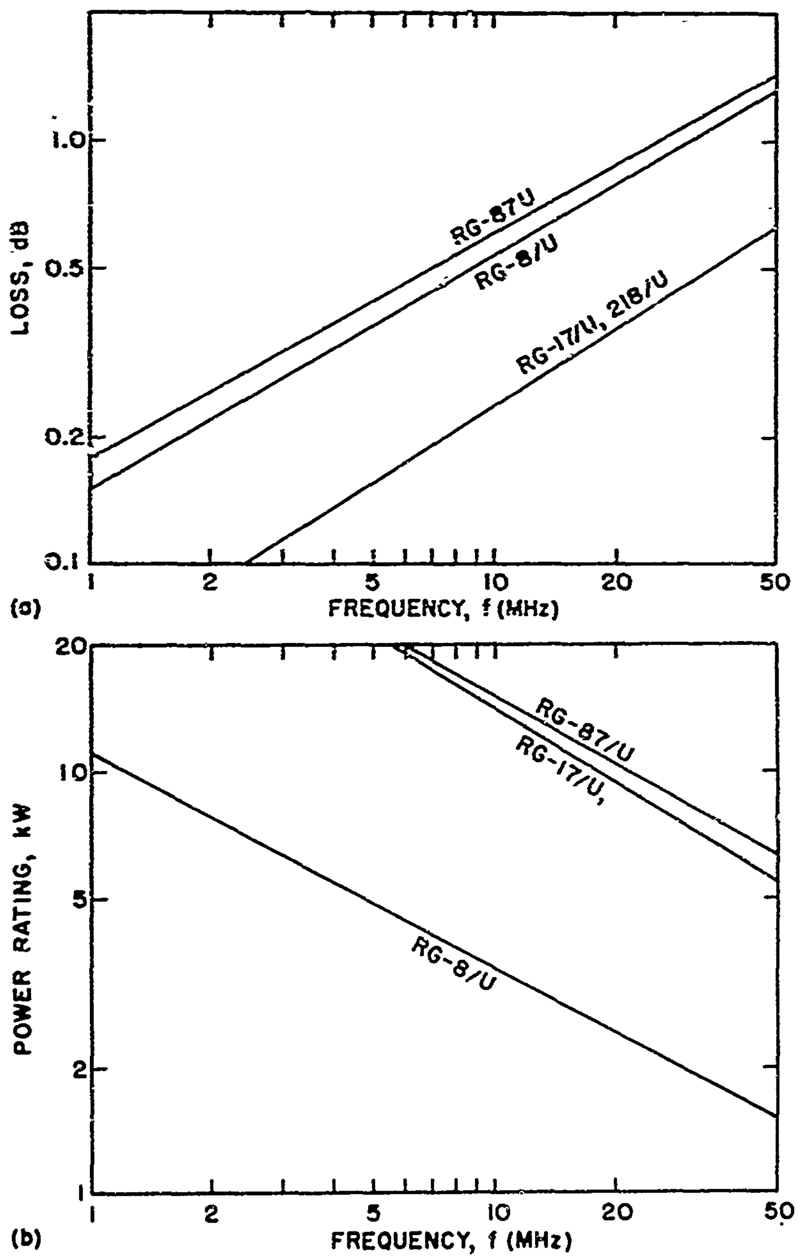


Figure 50. Properties of cables in HF range. (Data taken from Amphenol Catalog ACD-6.)

a. Loss, dB per 100 ft at 68° F and 1:1 VSWR.

b. Power rating at 104° F ambient temperature and 1:1 VSWR.

quickly corrode and become unreliable even in average weather, because of the dissimilar metals at the connections. This is especially critical when re-erecting a used antenna, since the various contacting surfaces will already be weathered. Several of the following recommendations are intended to help with this problem.

2. The coaxial cable should not be installed through the phasing lines until <u>all</u> other assembly steps, including the fastening of all jumpers between elements and phasing lines, have been completed. This will minimize the possibility of running screws through the cable jacket into the braid. (If desired, a "fish-line" can be strung through the phasing lines during assembly, then used to pull the coaxial cable into place.)

3. The 6-32 self-tapping screws, used throughout to fasten the phasing lines together at the joints and to fasten the jumpers from each element at the phasing-line end, are a definite weak point. The threads they cut are shallow, and they tend to work loose from the aluminum tubing, or to strip out when tightened down hard. On the other hand it is not permissible to use longer screws, or to use sheet metal screws with their deeper threads; the sharp points of the sheet metal screws are likely to damage the coaxial cable inside the phasing line. It is therefore recommended that machine screws be substituted for all the self-tapping screws, and that the holes be first tapped by hand in a separate operation. The machine screws must be no longer than the original self-tappers, but since their thread is full size nearly to the tip, they should do a better job of holding. Also they can be of larger diameter, up to size 10-32.

4. It is recommended that stainless steel screws and nuts be used at all electrical connections.

5. Since the phasing lines are too long to be made of a single length of tubing, each one has a butt joint in the middle. This joint is a source of trouble, since it is subjected to flexing and stretching while the antenna is being erected and while it is in service. Using larger machine screws as called for above will help to maintain good connection, but also a short jumper should be installed across each joint, with the usual precautions to maintain good contact.

6. On the upper antenna, the support-tube-to-boom brackets are not used for their original function, since the boom is supported in a different way. They should be installed, however, since they provide electrical connection between the two main booms.

7. As an extra precaution in high-wind areas, the telescoping sections of the elements in the vertical array, after being adjusted to length and clamped, may be secured by a 6-32 × 1/4 inch sheet metal screw in each joint.

4. ELECTRICAL CHECKOUT DURING AND AFTER ERECTION

Two types of tests should be made on the antennas during erection, and can be made at regular intervals afterwards to confirm their proper operation. These are a DC continuity test and a check of voltage standing-wave ratio (VSWR) over the operating frequency range. In addition, if the antennas are to be used for circular polarization, the sense of rotation of the upper antenna relative to the lower one must be noted, and the two feedline lengths must be electrically matched as described in Section 5 following.

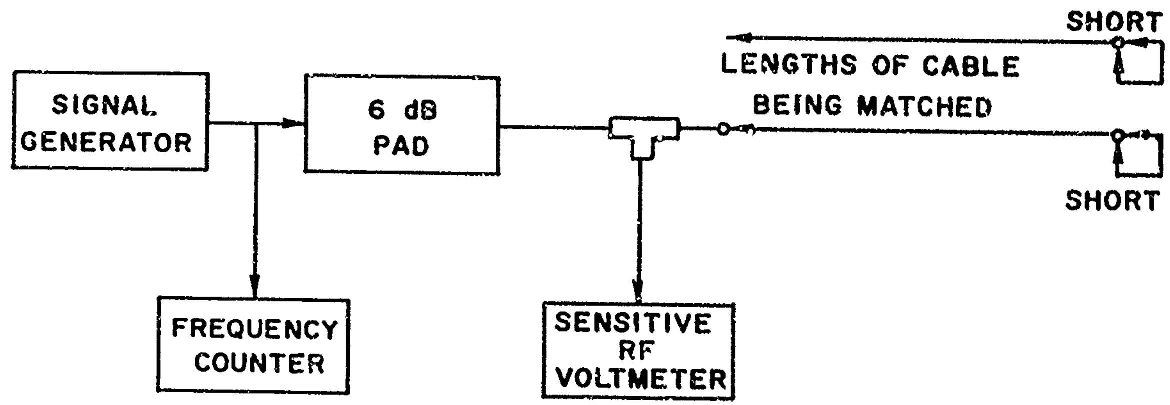
1. <u>DC continuity test</u>. This may be performed after assembly and installation of the feed cable, and both before and after erection. A low-range ohmmeter is connected between outer and inner conductors of the feed cable at its lower end. A reading of the order of 0.25 ohm (depending on the type and length of feed line) should be obtained, and should remain constant despite shaking of the antenna structure and connections. This verifies a large number of connections in the feed line and phasing line path, as follows: From feed cable connector through the center conductor of the feed cable to one short phasing line, through that phasing line butt joint, through the rest of that phasing line, through a jumper to one of the longest antenna elements, back through another jumper to the corresponding long phasing line, through the long phasing line with its butt joint to the jumper at the far end, through the jumper to the other long phasing line, back through that long phasing line with its butt joint, through another jumper to the other longest antenna element, through another jumper to the other short phasing line, through that phasing line with its butt joint to the outer conductor of the feed cable, back through the feed cable to the connector. Therefore this DC test verifies every electrical connection in the antenna except those from each element (except the longest) to a phasing line, and the joints in the elements themselves. These element connections can be separately verified with the ohmmeter before erection; after erection they may be verified by the VSWR test to be described. One other DC test should be made before erection; temporarily disconnect the outer braid of the feed cable from the phasing line through which the feed cable passes. The DC resistance should rise from about 0.25 ohm when connected, to infinity (many thousands of megohms) when disconnected, and should remain infinite despite shaking and jiggling of the feed cable. This will confirm that no screws are projecting through the cable outer insulation. Carefully restore the outer braid-to-phasing cable connection, and a reliable 0.25 ohm reading should again be obtained.

2. <u>VSWR check</u>. A direct-reading VSWR meter and an oscillator or signal generator covering the 12 to 30 MHz range are required. They should preferably operate at a signal level high enough (0.25 W or more) that stray signal pickup by the antenna is negligible. A preliminary test may be made with the array in its assembly position a few feet off the ground; the VSWR readings obtained will be a little higher than normal, but frequencies of excessively high VSWR can be located. The final test should be performed after the antenna is erected and in the clear, with crane booms, etc. removed from the immediate vicinity. The length of feed line between the antenna and the measuring point should be as short as possible. The indicated VSWR should be well above 2 to 1 at 12 MHz and below, dropping to below 2:1 at 13 MHz and remaining below 2:1 up to 30 MHz. The readings on an antenna in good condition will typically average 1.5:1 with small more-or-less periodic variations between 1:1 and perhaps 1.8:1. A large VSWR reading over a small portion of the range indicates a probable poor contact in the jumper or joints of an antenna element whose length is one-quarter wave near the frequency of worst VSWR. The approximate frequencies, allowing for jumper length, are as given below:

Element Number	Nominal Length Inches	Approx. Freq. MHz
D1	68 11/16	39.2
D2	76 5/8	34.5
D3	85 7/16	31.9
D4	95 5/16	28.2
D5	106	26.0
D6	118 1/8	22.9
D7	[illegible] 9/16	21.1
D8	146 1/2	18.7
D9	163 1/8	17.2
D10	181 1/8	15.3
D11	202 1/8	13.9
D12	225	12.7

5. FEEDLINE-LENGTH MATCHING FOR CIRCULAR POLARIZATION

When adjusting the relative phase of the horizontally and vertically polarized antennas (refer to Sections II-F and II-G in the body of this report) it is assumed that, except for the extra length of cable inserted in one feed line to obtain the desired phasing, the feed cables to the two antennas are carefully matched in electrical length. Matching of the feedlines should be carried out when the antenna is installed or whenever a line is changed; one inch of line has a phase shift of about one degree at 20 MHz. The lines should be cut to the same physical length to begin with, and all connectors and terminations made carefully alike. The feed cable on each antenna should be temporarily shorted at the point where it connects to the antenna phasing lines, the lengths measured electrically, and the longer cable trimmed as required. Time-domain reflectometry equipment may be used if available to measure the cable length. An alternative method which requires only a signal generator and a sensitive RF voltmeter or oscilloscope is illustrated in Fig. 51. The signal generator is tuned to a frequency that gives minimum voltage reading, indicating that the line is an integral number of half waves long at that frequency. When the two lines dip at the same frequency they are of the same electrical length. (This assumes that the lines initially have been cut closely enough to the same length that there is no possibility they have different integral numbers of half waves on them at the dip frequency. If in doubt, repeat the test at another frequency where a dip is obtained.) The exact frequency need not be known, but only the comparison between the frequencies at which the two feedlines dip. With care, feedlines 1000 ft long can be matched within ± one inch.



Note 1 - The frequency counter is a convenience, but, since only relative accuracy is required to match cable lengths, the counter is not necessary if the logging scale on the signal generator can be read to the required resolution.

Note 2 - The cables are shorted at the far end (in this case, the point of attachment to the antenna phasing lines) for this test. The shorting jumpers should be identical and installed alike.

Figure 51. Equipment setup for matching electrical lengths of coaxial feedlines.

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13. ABSTRACT

This report describes the design of a pair of HF antennas, one horizontally and one vertically polarized, whose gains and directivity patterns are reasonably alike over the range of elevation angles useful for oblique ionospheric propagation over typical one-hop distances. Means are given for obtaining the proper phasing for approximating circular polarization at a designated elevation angle and over a substantial frequency interval. The design must take into account the differing reflecting properties of ordinary ground for vertically-polarized and horizontally-polarized incident waves, and the variations of these properties with radio frequency.

The theoretical performance of a cross-polarized antenna pair of one particular configuration is described. It is shown that satisfactory performance should be obtained over ground having electrical properties within the range usually encountered, though not when the reflecting surface is fresh water, sea water or ground covered by a conducting screen.

Experimental results are given which tend to confirm that the crossed antenna pair does operate in the manner predicted by the theory. Construction details are furnished.

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BROADBAND						
CIRCULAR POLARIZATION						
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SUPPLEMENTARY

INFORMATION

August 1972

REVISIONS TO TECHNICAL REPORT NO. 153:

"An HF Antenna For Oblique Propagation Having Approximately Circular Polarization Over Appreciable Frequency and Vertical-Angle Intervals"*

by

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The report cited was published in July 1970. The main purpose was to demonstrate the capability for synthesizing nearly circular polarization at HF using cross-polarized log-periodic antennas (LPAs) over ground. It was concluded that such a scheme was a viable approach to the design of circularly polarized HF antennas. Moreover, it was stated "... that the operation of the antennas is little affected by the parameters (dielectric constant and conductivity) of the ground that forms the reflecting surface, for the normal range of variation of these parameters."

After publication of the report we discovered an error in the computer program that was used to obtain most of the curves for reflection coefficient and antenna elevation patterns. This error necessitates several changes in the theoretically derived characteristics of the antenna's behavior, which will modify our conclusion (quoted above) regarding the sensitivity of this behavior to the ground's dielectric constant and conductivity.

Specifically, it is now seen that the imaginary part of the complex dielectric constant (ϵ_{rc}) of the ground becomes significantly large compared to the real part for even below-average ground at high frequencies (3-30 MHz). It is quite obvious, therefore, that in most

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ENCLOSURE (1)

practical cases, ground-reflection coefficients must be individually calculated for the purpose of phasing the antennas to a given desired polarization.

It must be emphasized that the computer program error in no way affected the experimental results already obtained using this antenna (discussed in Chapter IV).

A. THE PROGRAM ERROR

The computer program that was employed to obtain the curves of reflection coefficient and most of the antennas elevation patterns used, by error, the following for Eq. (8a):

$$\epsilon_{rc} = \frac{\epsilon_2'}{\epsilon_o} - j\,\frac{\sigma_2}{\omega\epsilon_o\epsilon_r}$$

instead of the correct relation given in Eq. (8a) of the report, which is:

$$\epsilon_{rc} = \frac{\epsilon_2'}{\epsilon_o} - j\,\frac{\sigma_2}{\omega\epsilon_o} \qquad (8a)$$

This error may be viewed as changing the ground conductivity σ_2 to σ_2/ϵ_r.

Because of the error, the curves of reflection coefficient in Figs. 5 and 6 must be relabeled, and Figs. 7 and 8 must be done over entirely. The antenna elevation patterns of Figs. 9 through 14 and the curves of Figs. 16 through 20 all have a value for σ only one-tenth as large as marked--that is, they apply to antennas over "poor" to "very poor" ground rather than "good" ground. Likewise, in Fig. 15(a) and (b) the value of σ should be divided by ϵ_r. Also, the statement on pages 17 and 29 regarding the effect of ground conductivity on antenna patterns at HF and the conclusion on page 91 must be revised. These changes are listed in order below:

B. REVISIONS (ERRATA)

Page	Errata
15, Fig. 4	The verbal designations of the earth types on the bottom three curves should be revised to read: Rich Farm, Marshy Forest: Good Earth Residential: Average Earth Sand, Hills } Poor Earth Mountain, Rock } Industrial: Very Poor Earth
15, Fig. 4	Add "NOTE: These designations are somewhat arbitrary, and are used loosely to define the ground for calculations that follow."
17, Lines 10-18	Replace with the following text: "until "a" becomes larger than 0.3. However, Fig. 4 indicates that "a" is greater than 0.3 over most of the HF range, except for industrial-type (excessively poor) ground. Thus, in most practical cases the reflection coefficients will have to be individually calculated, using Eqs. (9) and (10). For cases where the reflecting surface is water or ground screen, a special situation exists, which will be discussed in Section K."
18, Fig. 5	Relabel all curves with values for $\sigma/\omega\epsilon'$ one-tenth as large. That is, "$\sigma/\omega\epsilon' = 1$ and 0.1" becomes "$\sigma/\omega\epsilon' =$ 0.1 and 0.01"; and "$\sigma/\omega\epsilon' = 3$" becomes "$\sigma/\omega\epsilon' = 0.3$", etc.
19, Fig. 6	Relabel all curves with values for $\sigma/\omega\epsilon'$ one-tenth as large. That is, "$\sigma/\omega\epsilon' = 1$ and 0.1" becomes "$\sigma/\omega\epsilon' =$ 0.1 and 0.01"; and "$\sigma/\omega\epsilon' = 3$" becomes "$\sigma/\omega\epsilon' = 0.3$", etc.
20, Fig. 7	New Fig. 7 enclosed herein.

Page	Errata
21, Fig. 8	New Fig. 8 enclosed herein.
24, Line 3	Change "a = 3" to "a = 0.3".
24, Fig. 9	Change "$a \triangleq \frac{\sigma}{\omega\epsilon'} = 3$" to "$a \triangleq \frac{\sigma}{\omega\epsilon'} = 0.3$". In second line of caption, change "good" to "poor".
26, Fig. 10	Change "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$", and "a = 1.4" to "a = 0.14". In second line of caption, change "good" to "poor".
26, Fig. 11	Change "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$", and "a = 1.1" to "a = 0.11". In second line of caption, change "good" to "very poor".
27, Fig. 12	Change "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$", and "a = 0.8" to "a = 0.08". In second line of caption, change "good" to "very poor".
27, Fig. 13	Change "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$", and "a = 0.65" to "a = 0.065". In second line of caption, change "good" to "very poor".
28, Fig. 14	Change "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$", and "a = 1.8" to "a = 0.18". In second line of caption, change "good" to "poor".
29, Lines 6-10	Replace with the following text: "The patterns of Figs. 10 through 14 were obtained using a constant "average" value of ground conductivity ($\sigma = 10^{-3}$ mhos/m). Where the conductivity is larger--say, $\sigma = 10^{-2}$ mhos/m, as in "good" ground--the horizontal-polarization patterns will be little affected, but in the vertical patterns the amplitude

Page	Errata
29, Lines 6-10 (cont.)	will decrease somewhat below the Brewster angle and increase above it. In Fig. 10 (at 13 MHz) the amplitude decrease will be less than 2 dB, at 7^{o} elevation and below, and the increase will reach less than 2 dB at elevation angles around 20^{o}. At 17 MHz (Fig. 11) the change will be about 1 dB, and less at higher frequencies. The effect on phase difference will be small (5 or 10 degrees) at 13 MHz. Variation of ϵ_r in ...".
29, Line 14	Change "$\sigma = 10^{-3}$" to "$\sigma = 10^{-4}$".
29, Line 24	Change "good" to "poor".
30, Fig. 15(a)	Change "$\sigma = 10^{-3}$" to "$\sigma = 6.7(10)^{-5}$, and "a = 0.09" to "a = 0.006".
30, Fig. 15(b)	Change "$\sigma = 10^{-3}$" to "$\sigma = 2(10)^{-4}$", and "a = 0.28" to "a = 0.056".
31, Fig. 16	In bottom line of caption, change "good" to "poor", and "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$".
34, Fig. 17	Change "good" to "poor" and "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$".
34, Line 4	Change "good" to "poor".
38, Fig. 19	Change, in captions, "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$".
39, Fig. 20	Change, in captions, "$\sigma = 10^{-2}$" to "$\sigma = 10^{-3}$".
40, Line 1	Change "good" to "poor".

Page	Errata
91, last para.	Replace with the following text: "It has also been shown that the operation of the antennas is little affected by variations in ground parameters, provided that a $\triangleq \sigma/\omega\epsilon' < 0.3$. However, from Fig. 4 it is seen that such a condition for "a" will not ordinarily exist over the HF band (3-30 MHz), except when the ground is sandy, hilly, rocky. or "industrial." If average or better ground is used, it will be necessary to calculate reflection coefficients individually, using Eqs. (9) and (10).

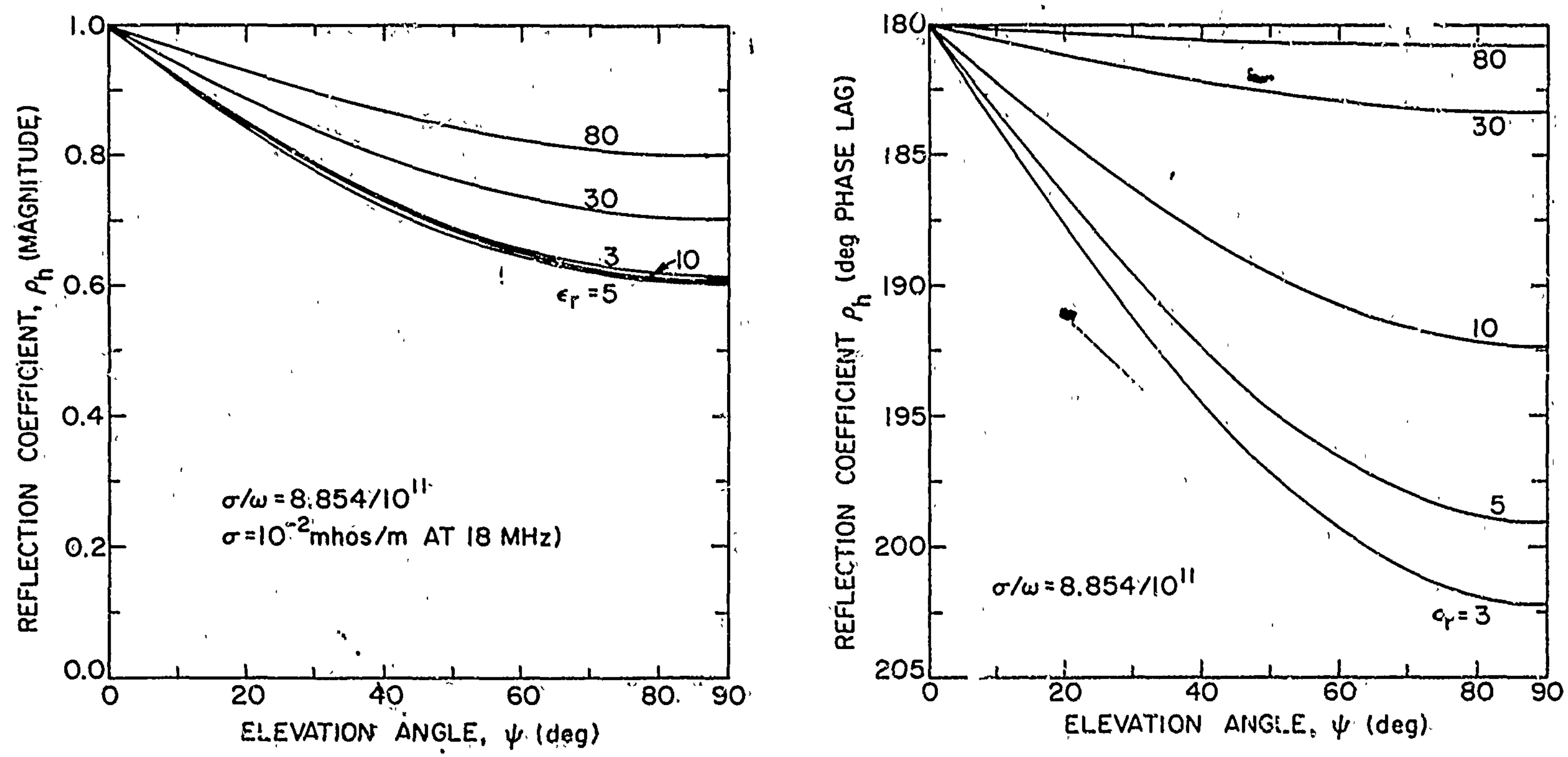

FIGURE 7 REFLECTION COEFFICIENT ρ_h FOR HORIZONTAL POLARIZATION. (As a function of ϵ_r.)

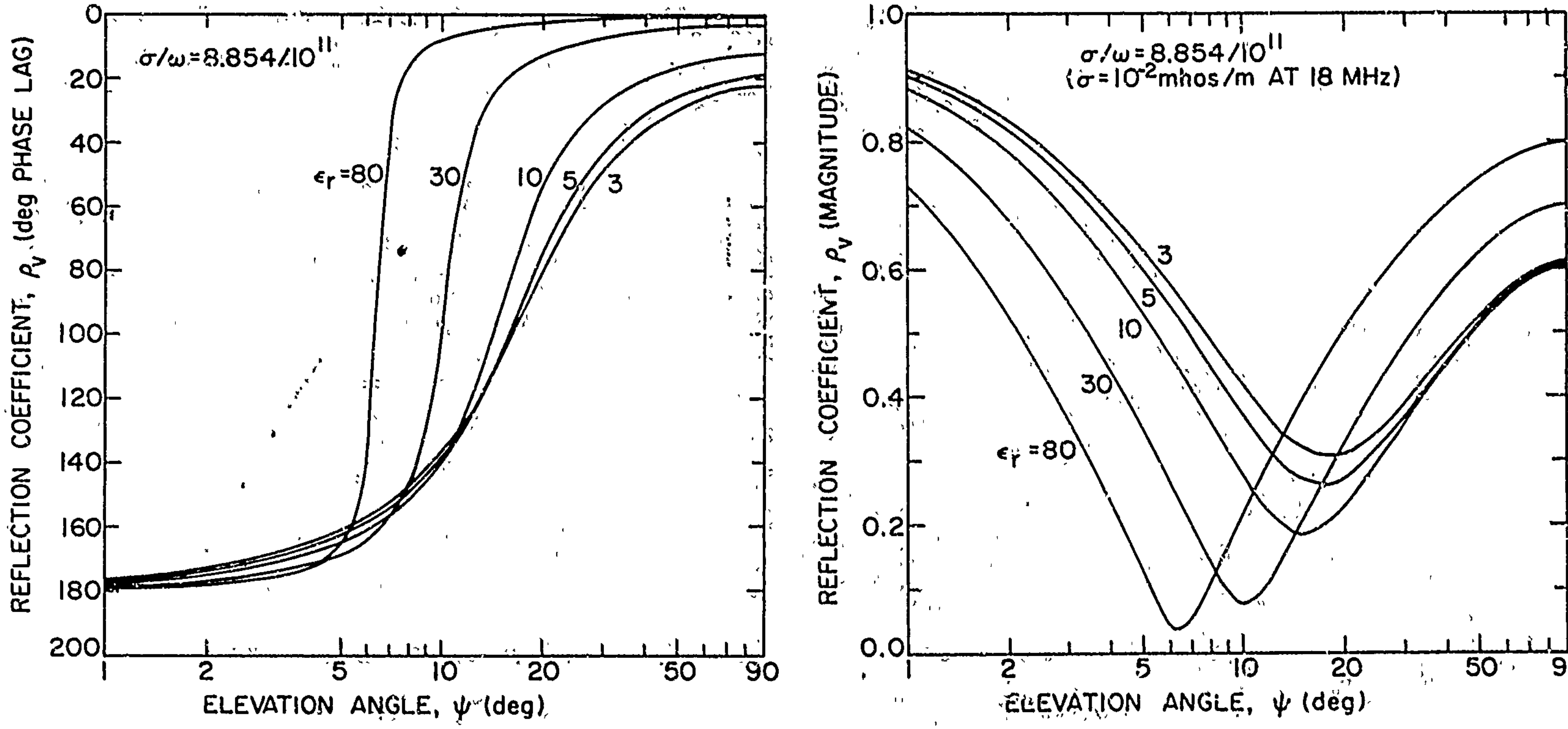

FIGURE 8 REFLECTION COEFFICIENT ρ_v FOR VERTICAL POLARIZATION. (As a function of ϵ_r.)